Climate and pro-glacial discharge interactions in the Pakitsoq region of Western Greenland.

Catherine Baggs
Lucy Cavendish College
June 2010

Scott Polar Research Institute
Department of Geography
University of Cambridge

This dissertation is submitted for the degree of Master of Philosophy

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. The Dissertation is no more than 20,000 words in length excluding the acknowledgements, declaration, list of references, tables, captions and appendices.

Table of Contents

List of Figures

List of Tables

Acknowledgements

Frstly I would like to thank the Sandy and Zorica Glen Charitable Trust for their generous support in part-funding my MPhil. Dr Ian Willis, for all of his support over the year and to Alison Banwell for always knowing where Ian is! The staff at SPRI has been amazingly helpful and my fellow MPhil students have provided a great sounding board when things don't go quite to plan.

Abstract

Over the past two decades coincident with Arctic climate warming, Greenland's glaciers have experienced significant volume loss with the resulting discharge substantially contributing to rising sea level. This change has occurred during a period of pronounced variability in regional climatology. However, the meteorological parameters forcing melting have not been well established, as there are few annual records of meltwater discharge directly from glaciers. To test how meltwater production varies in response to climate forcing, a multi-decadal proxy record of meltwater discharge was established for the Paakitsoq basin, Western Greenland and analysed statistically. The hydrological response of the basin changes through time during the spring and summer due to the variations in net radiation and air temperatures but also in snow cover, rainfall and the evolution of the glacier's hydrological system. The recorded time series of net radiation, air temperature and discharge was broken down into annual, seasonal and monthly time periods and analysed using statistical methods to assess the strength of the relationship between the variables. Correlation models show much stronger relationships between air temperature and discharge than net radiation although the correlations are never strong indicating that there are other variables influencing proglacial discharge regimes. In particular, the glacial hydrological system also only appears to be responsive to diurnal forcing following depletion of the seasonal snowpack

1.1 Introduction

The Greenland ice sheet (GrIS) plays an important role in regional and global climate (Nghiem et al., 2001). It contains around 7.4m global sea level equivalent and is vulnerable to ongoing anthropogenic change (Gregory et al., 2004). The most extreme scenario presented in the fourth report of the IPCC (2007) involves a warming of 8°C. However, even if the annual average temperature of Greenland increases by more than 3°C the global average sea level will be raised by 7m over a period of 1000 years (Gregory et al., 2004). Warming in Greenland caused by anthropogenic climate change will be larger than the global average as higher latitudes suffer the effects more due to the loss of snow and ice creating positive feedbacks (IPCC, 2007).

The world's great ice sheets were typically assumed to take hundreds to thousands of years to respond to external forcing. However within the last decade this assumption has been questioned as evidence has emerged suggesting that major changes in ice dynamics can happen on much shorter time scales. This rapid response in ice dynamics may have played a role in the doubled rate of ice sheet mass loss over the last decade (Rignot and Kanagaratnam, 2006). A future warmer climate would cause increased melting on glaciers and ice sheets. It is, therefore, desirable to understand how variations in climatic conditions will influence meltwater runoff from glaciers and ice sheets (Singh and Singh, 2001). The relationships between meteorological variables and proglacial runoff have been intensively studied (Singh et al., 2000, Hodgkins, 2001, Willis et al., 2002), although, for high latitude locations these relationships are not well-documented (Gurnell et al., 1994, Wolfe and English, 1995). Such studies are important as they can help to define how glacier runoff responds to climatic forcing allowing the potential future impacts of climate change on glacier dynamics and proglacial river runoff to be assessed.

This dissertation presents research into the meteorology and pro-glacial discharge interactions in the Paakitsoq region of Greenland as the links between the hydrology and glacial dynamics are not yet known over longer time scales (van de Wal et al., 2008). It is a research project that integrates both meteorological and discharge data and analyses the correlations between them over different time scales using statistical methods. Considering the existing literature on the Paakitsoq basin and the documented relationships between meteorological variables and glacial discharge and, the dissertation aims to show the extent to which air temperature and net radiation are controlling factors on the magnitude and patterns of daily and seasonal discharge cycles and the extent to which this control varies from year to year.

1.2 Aims and Objectives

The distinctive characteristics of glacierized basins have important implications for (i) runoff regimes; (ii) water storage and release; (iii) the incidence of flooding and (iv) the effects of climate variability and change on these (Willis, 2005). The overall aim of this research is to examine how characteristics of one particular glacierized basin influence these four aspects of its hydrology. More specifically, the objectives are:

- investigate the statistical relationships that exist between meteorological and discharge data on monthly, seasonal and annual time scales.
- Analyse three hourly lags between peak temperatures and peak discharge and how these change through time.
- infer the characteristics of the basin hydrology.

Two data sets from Asiaq and the Greenland Climate Network (GC-Net) have provided discharge data from a land terminating glacier and meteorology stations across the ice. These will be used to analyse the correlations, differences and lags between net radiation, air temperature and glacial discharge on monthly, seasonal and annual time scales. Although this will not provide direct evidence of the routing of meltwater through the glacier, the lag times between meteorological variables and discharge will give an indication of the water storage processes taking place and how these processes vary monthly, seasonally and inter-annually.

The relationship between air temperature and discharge might be expected to change over the summer with a more sluggish hydrological response in the early summer and a more rapid response later. There may be a significant threshold in the seasonal cycle and this dissertation aims to find out if a change occurs, if so, when it occurs, and if the timing varies from year to year.

1.3 Study Area

The margin of the Greenland ice sheet near Paakitsoq has been the subject of a large number of glaciological studies and is still an area of international research activities. The early work in the region was mainly carried out due to relatively easy access onto the ice sheet margin and for its potential to generate hydroelectric power.

The basin is around 45km north-east of Jakobshavn Isfjord (Figure 1.1 and 1.2) and has a catchment area of 326 km², of which 286 km² is ice covered (see Table 1.1). The drainage basin contains four outlet glaciers from the inland ice (inventory numbers 1GE0700 1 & 2 and 1GE0400 1 & 2), which flow into three proglacial lakes, Lake 233, Lake 326 and Lake 187. Lakes 233 and 326 subsequently drain into Lake 187, which then drains to the sea. Lake 187 has had a discharge monitoring station since September 1983. Hydroelectric power (HEP) companies have promoted long-term measurements of glacial discharge at this site but the data have seldom been analysed with regards to glacial hydrology. The glaciers have retreated since 1880 (Wiedick, 1968) but the drainage configuration is thought to have been stable for over 40 years (Kern-Hanssen, 1988) therefore it is reasonable to assume that the drainage patterns on the ice are semi-permanent. Drainage takes place in the same supraglacial stream system on the ice from year to year because the surface topography is controlled largely by ice movement over the undulating subglacial terrain. Comparisons of aerial photographs from 1986 and a 1988 map produced from them with older aerial photographs from 1948 and maps from 1959 show a stable supraglacial drainage pattern with rivers draining in the same locations and moulins in the same positions despite considerable glacier thinning (Thomsen, 1988). Furthermore, a comparison of the 1988 map with 2001 Landsat imagery also shows that the drainage configuration is very stable over time.

Catchment	Icefree area	Icecovered area	Lake area
Sø 233	17.7 km^2	234 km^2	2.2 km^2
Sø 187	11.6 km^2	47 km^2	3.2 km^2
Sø 326	4.1 km^2	4 km^2	2.3 km^2
TOTAL	33.4 km^2	285 km^2	7.7 km^2

Table 1.1 Hydrological catchment areas of the Paakitsoq lakes (Source: Kern-Hansen, 1988)

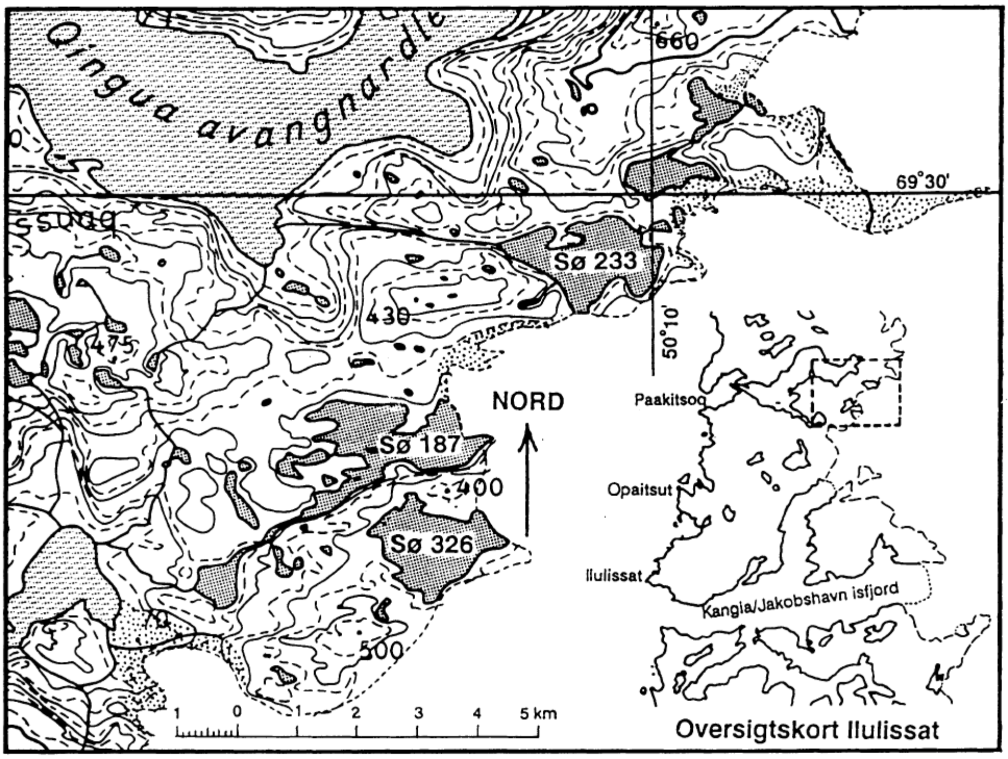


Figure 1.1

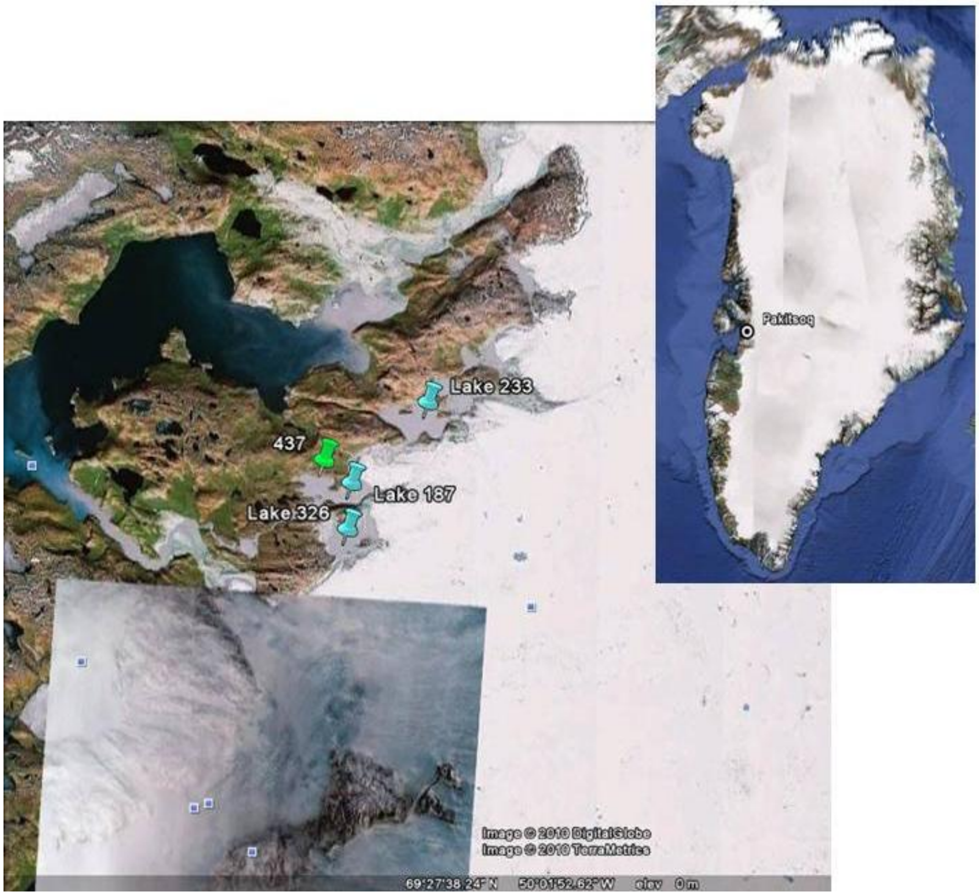


Figure 1.2

Figure 1.1 Drainage basin at Paakitsoq. (Source: Kern-Hanssen, 1988)

Figure 1.2 Google Earth representation of the lake locations and automatic weather station.

1.4 Previous Research

At present approximately 57% of the precipitation that falls over Greenland melts and runs off as water (Hanna et al., 2005). Although a warming climate is expected to produce higher temperatures and more precipitation, many studies agree that the increase in melting will be greater than the increase in precipitation (Gregory et al., 2004). Modelling studies have shown that for every 1°C rise in surface air temperatures, 20-50% more meltwater is produced from the GrIS (Janssens and Huybrechts, 2000, Hanna et al., 2005) and satellite data shows an almost parallel increase of 47%/°C in snowmelt extent (Abdalati and Steffen, 2001). Surface melt across the Greenland ice sheet accelerated in the late 20th/early 21st century coinciding with the rapid decline of Arctic sea ice (Maslanik et al., 2007). It is a sensitive indicator of climate variability and this was demonstrated by the observed reduction the melt area after the eruption of Mt Pinatubo, Philippines, in 1991 (Abdalati and Steffen, 1997).

In recent years, many studies have analysed changing trends in Greenland's surface melt extent and duration. They all reach similar conclusions; over time surface melt is expanding and lasting for longer during the summer season (Figure 1.3).

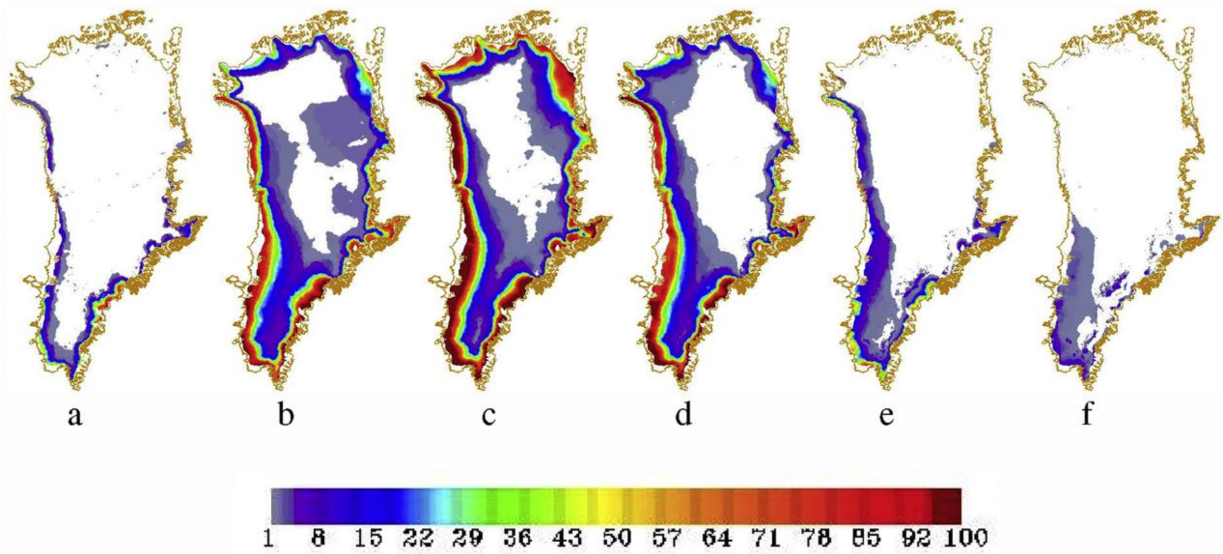


Figure 1.3. Monthly mean melt extent and occurrence (%) in (a) May, (b) June, (c) July, (d) August, (e) September, and (f) October. White represents areas that experienced no melt in that month. (Wang et al., 2007)

Since 1988 the cumulated melt extent on Greenland has increased by almost 30% (Wang et al., 2007). This trend agrees with recent observations highlighting rapid and substantial changes on the GrIS due to a warming climate (Krabill et al., 2000, Hanna et al., 2008, Zwally et al., 2002). There are currently several studies that have analysed the changes in surface melt and they are in agreement that melting is increasing and that there is a need to continually monitor the changes in order to assess the impacts that climate change is having on the Greenland Ice Sheet. Recently evidence has emerged from Bamber et al., (2007) to suggest that changes in glacial dynamics occur on shorter time scales than originally thought; regional oceanic and atmospheric warming have been suggested as being responsible for the rapid responses but it has not been possible to separate the influence of these two forcings. There is also now substantial evidence from Joughin et al., (2008) and Holland et al., (2008) showing that the warm Irminger ocean current is likely to be the main cause of retreat, acceleration and lowering of ocean-terminating glaciers but Zwally et al., (2002) and Shepherd et al., (2009) have shown land-terminating glaciers respond dynamically to short term changes in surface hydrology, presumably through changes to subglacial water pressures due to sudden drainage of supraglacial lakes through crevasses (i.e. hydrofracturing)(Das et al., 2008). However the links between the hydrology and glacial dynamics are not yet known over longer time scales (van de Wal et al., 2008).

Glacial Drainage

Flowing water in glacial environments exerts an important influence on glacier behaviour and geomorphological processes. Water may enter the drainage system from melting snow or ice, rainfall or the release of stored water. Surface melting of ice and snow exhibits pronounced daily, seasonal and random variations according to the local energy balance, causing marked fluctuations in the runoff. Although englacial and subglacial melting can also occur as a result of frictional heat generated by deforming or sliding ice, geothermal heat and pressure melting associated with glacier flow over the bed, overall, the basal melting is more constant through time and contributes little to the variations in runoff from glacierized catchments. The build up and release of stored water (subglacial, supraglacial, or englacial) exerts a very strong influence on runoff and can cause very high magnitude flood events (Benn and Evans, 1998) which can increase subglacial water pressures thus forcing a rapid change in the subglacial drainage configuration.

When melting exceeds re-freezing rates, water will accumulate in the snow pack and where this snow is on a slope, water will flow laterally through the snowpack eventually forming rills which join up to form a dendritic drainage network. These networks can exist entirely within the snow but if discharge is high enough, then surface channels form. These networks are often well developed on glacier ice owing to its impermeability. Subglacial water movement is generally through dendritic conduits, linked-cavity networks or darcian porewater flow (Benn and Evans, 1998) and each different system will allow water to flow to the ice margin at different rates thus affecting the lag time between meltwater production and the water exiting the glacial system. Recently integrated models of glacial drainage have been developed which allow spatial and temporal variation in runoff to be predicted from catchment topography and meteorological inputs, although this has not yet been done for the GrIS.

Seasonal patterns of discharge variation and meltwater storage have been investigated since 1969 (Wiedick, 1968). Previous research has focused on the impact of climate change on glacier mass balance and glacier size variations and far less attention has been paid to the effects on glacier discharge. One of the major problems in the interpretation of climatic and hydrological data is a lack of reliable long-term records and the available studies of glacier discharge have focused on diurnal to seasonal time scales in mainly Alpine valley glaciers. Typical characteristics of glacier runoff involve clear melt-induced diurnal cycles and a concentration of annual flow during the melt season (Hock, 2003). These studies have however improved the understanding of the processes governing meltwater generation and drainage (Fountain et al. 1996; Gordon et al., 1998).

Controls on Glacial Drainage

Hodgkins, (2001) stated that the meteorological inputs to a catchment that drive surface melting are translated into runoff outputs which are then mediated by the glacier's hydrological system. The primary control on the hydrological regime in any glacial basin is the supply of energy for melting (Hodson et al., 1998). This energy ultimately controls the air temperatures and many studies have used air temperature data as a proxy for energy (Sicart et al., 2008). The energy supply to and its subsequent utilization in high latitude, low altitude glacial environments is very different to that in low latitude, high altitude basins. A major difference is that incoming radiation is continuous during the summer months keeping temperatures fairly stable and dampening the diurnal signal for all variables (Hodson et al., 1998).

Proglacial discharge is controlled by meltwater processes and its subsequent routing which depends on the geometry of the glacial. Variations in proglacial discharge are dependent on meltwater flows and the seasonal evolution of the supraglacial, englacial and subglacial drainage systems (Jobard and Dzikowski, 2006). One of the main characteristics of glacial drainage systems (supraglacial, and subglacial) is the rapidity of their re-organization during the ablation season (Gordon et al., 1998). Work on Haut Glacier d'Arolla and other glaciers suggests that early in spring a glacier is underlain mostly by a distributed hydraulically inefficient linked cavity system which then evolves into a more hydraulically efficient channel system (e.g. Nienow et al, 1998; Swift et al., 2005). The increasing size and efficiency of the cavities modifies the movement of water through the glacier thus influencing the proglacial discharge pattern.

Snow and firn act as aquifers on a glacier serving to dampen discharge peaks and reduce the amplitude of the diurnal flow variability. Nienow et al., (1998) discovered that when the snow line retreats, subglacial drainage is thought to switch from a distributed to a channelized system. Early season melt is temperature dependent (Shea et al., 2005), when the snow cover is deep and the hydraulic properties of the snowpack limit diurnal discharge variability, there is a slow hydrological response. As the melt season progresses the migration of the transient summer snow line and ripening of the snowpack induce a glacier wide decrease in albedo and increased surface melting which will impact heavily on the routing of water across the glacier surface. The difference between the amount of surface water and snow can be seen in the LandSat images (figures 1.4a and 1.4b). The July 2001 image shows high snow cover and several supraglacial lakes indicating that whilst the snowpack is still present, it is saturated and melting. In August 2001, the presence of dark ice indicates that most of the snow had melted. There are also fewer supraglacial lakes as the drainage system has evolved and is now more efficient at transporting water to moulins and into the subglacial drainage system or directly across the ice to the ice margin.

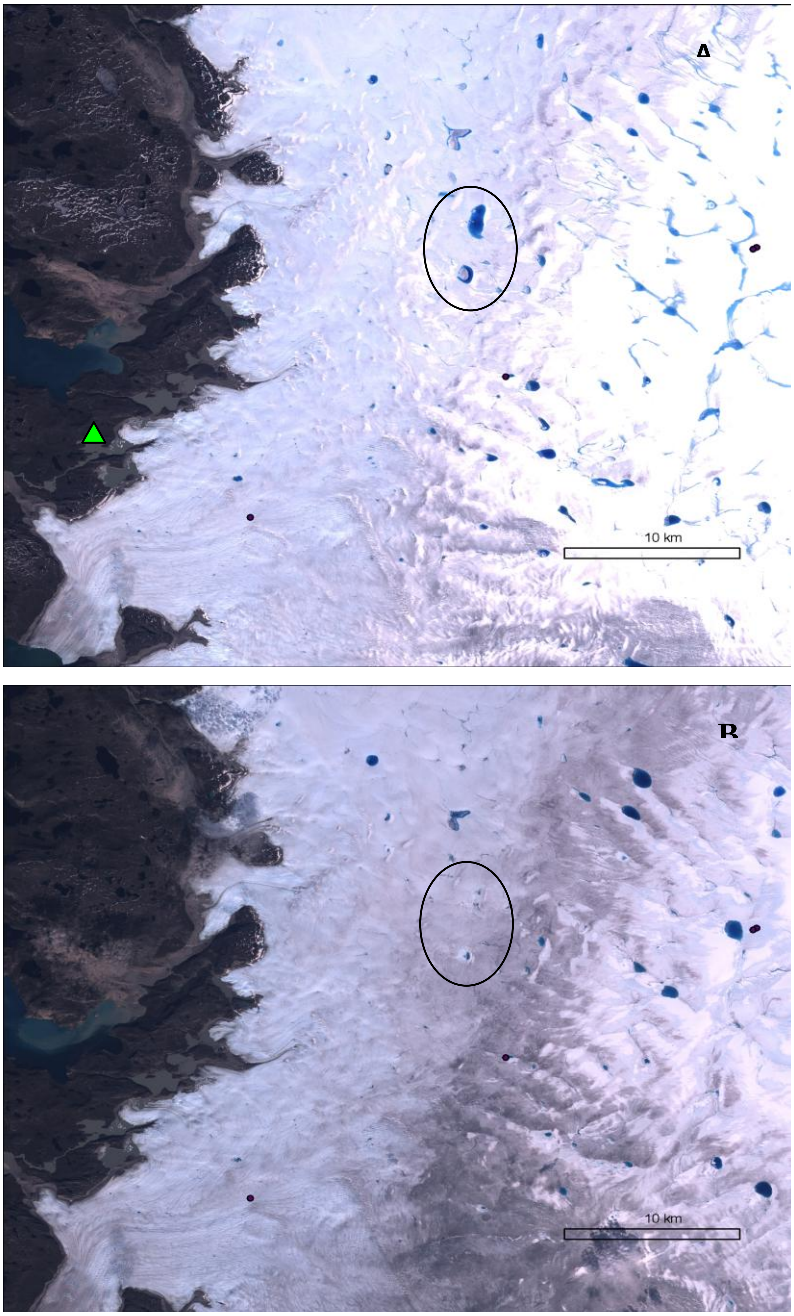


Figure 1.4 Landsat images of the Paakitsoq study area. The green triangle indicates the location of lake 187 and AWS 437. The circled areas identify a large lake and an ice-capped lake that change significantly between the photographs. (A) image collected July 7th 2001 (B) image collected August 1st 2001.

Glaciers temporarily store water on many different time scales (Jansson et al., 2003), the release from storage being controlled by both climate and internal drainage mechanisms and pathways. Climate warming is expected to prolong melt seasons, thus reducing annual discharge variations but increasing the total amount of annual runoff (Hock, 2005). In addition, diurnal discharge fluctuations will, at least in an initial phase be amplified by enhanced daily melt water production and a more efficient transport network through the glacier (Braun et al., 2000; Willis et al., 2002,).

Short term discharge fluctuations are common in proglacial measurements as the result of changes in water storage or short-lived events. Periodic glacier flow instabilities such as surges may be linked to temporal changes in the morphology of subglacial drainage systems (Kamb, 1987) and have been sometimes attributed to ice-cliff collapse, river damming, subsequent dam failure or flood release (Ballantyne and McCann, 1980). Other short term variations in discharge may arise through the release of water stored supraglacially, englacially or subglacially and this may account for breakdowns in the correlation between air temperatures and discharge. Ballantyne and McCann (1980) described discharge fluctuations resulting from temporary damming of glacial meltwater conduits and the subsequent release of meltwater. They described three main types of discharge fluctuation as illustrated in figure 1.5.

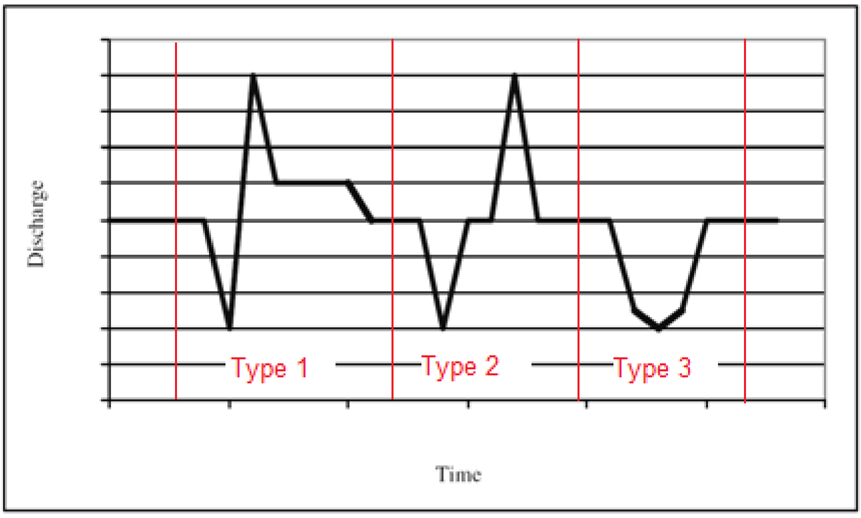


Figure 1.5: The three types of short term discharge fluctuations as described by Ballantyne and McCann (1980) in their work on Ellesmere Island, Canada. (Source: Stott and Grove, 2001)

Type 1: An abrupt fall in discharge followed immediately by an equally abrupt and brief rise to a level higher than that preceding the initial fall, this could be attributed to ice damming and then a subsequent breach of the dam.

Type 2: An abrupt fall in discharge succeeded by a brief return to the previous rate of flow, then a sudden and brief rise to greater discharge. This might happen in situations where an ice dam is overtopped and a steady rate of discharge prevails before its sudden failure.

Type 3: An abrupt fall in discharge quickly followed by a return to previous rates of flow with no apparent increase in discharge above "expected" levels although the stage trace may remain unsteady for some time afterwards. After a sudden damming from potential ice collapse or debris fall very slow debris removal will cause varied discharges.

(Ballantyne and McCann, 1980, Stott and Grove, 2001)

<u>Time Series Models and Analysis</u>

There are two approaches to modelling glacial hydrology; the forward modelling approach as used by Arnold et al., (1998); Nienow et al., (1998); Willis et al., (2002); and Boon and Sharp, (2003) and the inverse modelling approach that uses statistical analysis to look at the relationships between meteorological and discharge time series (Hodson et al., 1998; Hodgkins, 2001; Lafreneire and Sharp, 2003; Shea et al., 2005) .

Glacial hydrology has been modelled on many temperate glaciers, especially the Haut Glacier d'Arolla, Switzerland where many studies have concentrated on the effect of snowpack removal during the ablation season on supraglacial, englacial and subglacial drainage. Richards et al., (1996) showed that the seasonal retreat of the snowline alters the volume and spatial patterns of water input to the system causing reorganisation of the basal drainage network, at the Haut Glacier d'Arolla, as the melt season progresses. The Arolla project had far-reaching implications for predicting runoff in glacierized catchments under changing climatic regimes and highlighted the need for similar work to be carried out. Arnold et al., (1998) calculated the meltwater production over the entire surface and then routed it over the surface and subglacially. The model showed that the presence of the snowpack delayed the reorganisation of the subglacial drainage system. Willis et al., (2002) determined the effects of the up-glacier retreat of the snowline on spatial and temporal melt patterns and the subsequent routing of the water through the Haut Glacier d'Arolla to the margin using a melt model based on energy balance theory. The removal of the snowpack was seen to increase daily discharges by ~50% and maximum discharges by 300%. It also reduced the lag time between peak melt rate and peak discharge from 3 hours to 51minutes, however the Swiss glacier is small and relatively steep compared to the Paakitsoq basin so lags this small are not expected to be seen in the data.

Alison Banwell (Scott Polar Research Institute) is currently developing a numerical model as part of her PhD research that can be used to predict spatial variations in melting across the Greenland Ice Sheet, storage and routing of water in snow or firn and then routing of the water englacially and subglacially to the ice sheet margin. The key thing is that her work is a forward modelling approach which can take climate and predict proglacial discharge for given assumed configuration of a drainage system. The work of Sylvan Long (Scott Polar Research Institute – MPhil 2008) contributed to this by using a subglacial drainage model to replicate observed and theoretical aspects of subglacial drainage beneath the GrIS margin. The model supports the work of Zwally et al. (2002) and the correlation between melt input and ice sheet acceleration but it also predicts that capped conduit flow constrains the amount of meltwater that can enter the system which has not been documented within the valley glacier studies.

Inverse modelling has been carried out using time series statistical analyses. Gurnell et al. (1992) explored patterns in the hydrological and climatological time series from the Haut Glacier d'Arolla basin in Switzerland estimating time-series models for subperiods of the melt season. They interpreted the results of a time series model to reflect a progressive transition from snow-melt to ice-melt dominated drainage that resulted in a rationalization of the glacier's drainage system. The work of Singh et al. (2000) is also important due to its use of lag correlation in evaluating the relationships between meteorological parameters and discharge. One of their aims was to examine the seasonal evolution of lag correlation relationships and to identify the physical processes responsible for the changes. This research, however, focused on a glacierized basin in the Himalaya and therefore the observed relationships would be expected to be very different to those observed at high latitudes. Similar to Jensen and Lang, (1973), Singh et al., (2000) divided the discharge record into monthly intervals and found that the lag times between air temperature and discharge varied throughout the melt season.

Relationships between meteorological variable and discharge in Valley Glaciers

Hock et al, (2005) suggest that most annual discharge will be concentrated during the summer melt season and amounts will be negligible in winter when most precipitation is stored as snow. This is exacerbated during the Arctic summer due to more daylight hours, and the lower albedo of ice compared with snow (caused by relatively low snow accumulation over the winter when compared to temperate glaciers). Analysis of the relationship between meteorology and the monthly, seasonal and inter-annual patterns of runoff should reflect the varying functionality of that particular system with the role of water storage likely to be of significant importance.

On several valley glaciers, seasonal variations in liquid water storage and release have been examined using a water balance approach. Most studies have shown that water is stored during spring and early summer and then released. Tangborn and Rasmussen, (1976) investigated the water balance and meltwater pathways within the South Cascade Glacier in Washington, USA. It was suggested that during times of no melt in the autumn and winter, that the meltwater channels within the glacier closed off by deformation causing water to be stored in spring and early summer. New meltwater inputs in the spring re-opened these pathways by the melt of basal ice and the stored water was released. Other studies (Haut Glacier d'Arolla, Midre Lovenbreen and Mikkaglaciaren) have shown that the annual amount of water discharged from the glacier is greater than that produced over the summer melt season implying that additional water must have been stored before measurements began, thus confirming the findings of Tangborn and Ramussen, (1976).

Nienow et al, (1998), used dye tracing techniques to investigate change in the englacial and subglacial drainage systems from the ablation seasons of 1990 and 1991. The removal of snow by melting (with its high albedo and water storage capacity) from the glacier surface lead to a dramatic increase in the volume of runoff into moulins and the peakedness of diurnal discharge cycles. This produced high transient water pressures within the drainage system causing it to evolve rapidly into a channelized system. If this also happens in the Paakitsoq basin, then it will be possible to pinpoint the date when the snowpack has melted by looking for the transition to diurnal cycling in the discharge data.

Seasonal runoff regimes are controlled by the changing amounts of net radiation and air temperatures over the seasons. Gurnell et al. (1994) compared discharge from the Alpine Haut Glacier d'Arolla and the Arctic Austre Brøggerbreen, Svalbard. In the Alpine basin, discharge followed a distinctive seasonal sequence driven by changing surface albedo and air temperatures. The same sequence was subdued in the Svalbard basin and heavily modified by the influence of air temperatures on melt rates. Hodgkins', (2001), research on Scott Turnerbreen in Svalbard found that there was a clear transition date in the middle of the melt season, in the early part of the season until mid-August 80% of the total summer discharge left the catchment. The remaining 20% was discharged later in the season. The bulk of the seasonal discharge occurred during a relatively short time period with high variability which started and ended rapidly between mid-July and early August. Prior to this transition, proglacial discharge was high and variable and mean hydrographs showed little indication of a diurnal cycle. Following the transition, the proglacial discharge was low and constant but showed evidence of a more pronounced diurnal cycle. Hodgkins's (2001) research into a non-temperate glacier in Svalbard, shows evidence that the glacier's hydrological system appears to respond to diurnal forcing only following the depletion of the seasonal snowpack as a meltwater source. Significant contributions from groundwater can also be ignored because of the presence of permafrost at high latitudes.

Braun and Escher-Vetter (1996) found an increasing trend in annual discharge from Vernagtferner, Bavaria, associated with a period of sustained negative net balance, during which the total glacier area decreased between 1979 and 1990. They also found that the amplitude of diurnal discharge variations increased. They attributed these changes to an increase in the area of exposed bare ice relative to snow and firn, which would reduce the albedo and increase melt rates, and would also increase the amount of meltwater following rapid drainage paths to the glacier snout. Moore and Demuth, (2001), found using a multiple regression model, when analysing meteorological variables and discharge variability at the Place Glacier, Canada for monthly periods between 1969 and 1989, July was the only month when the temperatures for the preceding and current month were significant predictors of discharge. For August, winter mass balance and the current month’s temperature were significant. Their only apparent observed trend in discharge data was a decrease in August runoff (other months fluctuated) and this contrasts with the findings of Braun and Escher-Vetter (1996) who found a clear increasing trend in August’s glacier discharge.

Wolfe and English, (1995) examined meteorology and runoff from a small catchment on Ellesmere Island, Canada on a daily basis using a multiple regression model. Air temperature on rain free days gave the best correlation with discharge although rainfall events dominated the discharge cycle during the period of ice melt and this significantly reduced the accuracy of the discharge predictions. Hodgkins, (2001) found that there was a daily discharge minimum at 06:00 and a maximum at 18:00 but the form of the average hydrograph was somewhat irregular with several peaks and troughs throughout the diurnal cycle.

Overall the statistical analysis of Hodgkins (2001) showed a switch from air temperature exerting no control over discharge to it affecting the discharge produced. This is very different from an Alpine glacier (Gurnell et al., 1992, Gurnell et al., 1994) where the correlation between air temperature discharge was better correlated as the melt season progressed. Hodgkins (2001) tried to explain the temporal variation in magnitude and variability of discharge and its response to meteorological inputs with regard to the seasonal meltwater storage cycle. In the first part of the melt season the release of supraglacially stored water dominated the hydrograph. This water was not responding to energy fluxes at the diurnal timescale as it was produced before the peaks and troughs in meteorological inputs. In the latter part of the season, most of the supraglacial water has been discharged. With little storage occurring on the glacier surface, surface melting contributed to the hydrograph on a diurnal scale and the system appeared more responsive to meteorological inputs.

Greenland Ice Sheet

Melting on the GrIS generally starts in May and lasts until August or September, with greatest runoff in July and August (Figure 1.3). Transect analysis of meltwater production at different altitudes shows that the amount of meltwater produced decreases with altitude mainly due to lapse rates and the decrease in temperature (Oerlemans et al., 1999). The first phase of melting at any elevation involves the removal of winter snow cover followed by melting of the glacier ice. Runoff from melting ice is almost instantaneous while runoff from melting snow may be hindered, for example, water from melting snow can be refrozen so it will not contribute to runoff but will form ice lenses or superimposed ice. There are also large areas of the ice sheet with relatively gentle slopes where meltwater can be stored in supraglacial lakes or slush fields (Braithwaite et al., 1992).

.

2. Methodology

The data that are available to analyse for this study have been provided by GC-Net and Asiaq. Asiaq is a Greenland government organisation and operates all over Greenland, undertaking activities concerning the physical environment. GC-Net, a project sponsored by NASA is the Greenland Climate Network. There are almost continuous discharge readings from Lake 187 and air temperature readings from station 437 on the shore of Lake 187 (Figures 1.1 and 1.2). The net radiation data are only available between 1999 to 2006 (figure 2.1)

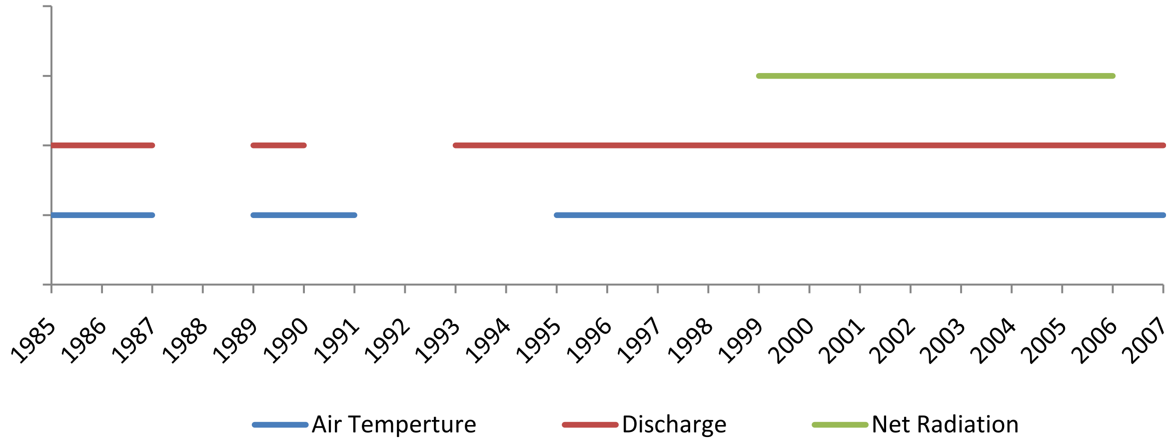


Figure 2.1 Data availability from the discharge monitoring station at Lake 187 and the Automatic Weather Stations (AWS) at 437 and JAR 2.

Due to the incomplete time series', the data have been analysed biennially and the odd years were used (1985-2007). This was done to standardize the results and to ensure an even spread of data. The net radiation data were analysed with the discharge and air temperature for years 1999, 2001, 2003 and 2005. Due to there being very little discharge in the winter, the data was only analysed during the ablation season of May – September.

2.1 Discharge and Air Temperature

Lake 187 has a discharge and climate monitoring system that has been active since the early 1980s. Stage measurements are collected every 3 hours and discharge readings are calculated using an empirical stage discharge relationship. The data are transmitted by modem from the climate stations to Asiaq, where they are quality assured. The recorded time series are shown in figure 2.1.

2.2 Net Radiation

GC-Net automated weather stations (Figure 2.2) are located at 20 locations on the Greenland ice sheet, and the net radiation data produced at JAR 2 are being analysed in this study. They have been active since 1999 and collect data at hourly intervals. Despite making use of well-recognized and reliable sensors, the harsh climate of the Greenland ice sheet makes it difficult to obtain continuous data sets. The quality-control task is complicated further by the fact that up to 20% of the data are not transmitted.

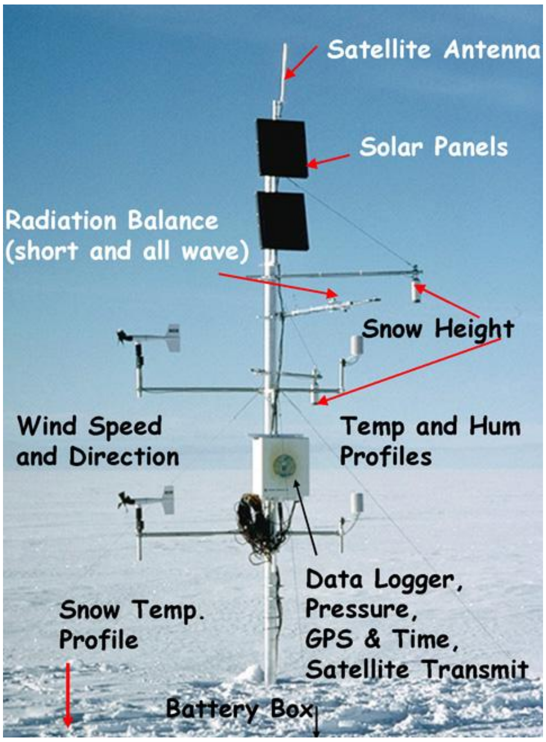


Figure 2.2 GC-Net Automatic Weather Station. (Source: Konrad Steffen)

The radiation, air temperature and discharge signals are not expected to coincide exactly as melt water must travel through supraglacial, englacial or subglacial pathways before arriving at the discharge measuring station. There are also other potential sources to melt water that will not react to meteorological forcing, such as geothermal heat, sliding friction heat and dissipation of strain energy. As well as the potential of a contribution from any water stored previous to the month of May each year, to be taken into account. However the contribution from groundwater can be neglected due to the high latitude and the presence of permafrost. The most significant contribution to the glacial discharge will be from melting snow and ice which is often strongly correlated with air temperature and net radiation; it is these relationships that are explored here.

2.3 Statistical Analysis

Several authors have used statistical analysis to look at the relationship between hydrology and meteorology in glacierized catchments (Hodgkins, 2001; Moore and Demuth, 2001; Hock et al., 2005) although not for the GsIS. Some studies have derived different results for different sub-periods using linear regression by splitting the observations into the rising and falling limbs of daily discharge hydrographs (Fenn et al., 1985), early and late ablation season (Richards, 1984, Fenn et al., 1985) or rainfall and rain-free periods (Fenn et al., 1985, Richards, 1984). Because these distinctions are subjective (Willis et al., 1996; Moore and Demuth, 2001) it was decided not to pursue these possibilities and to make distinctions using monthly time periods. This research also puts heavy emphasis on the relationship between discharge and air temperature since it is this element that has proved to be the most important variable in previous regressions of meteorological factors on glacier discharge (Lang, 1968). Braithwaite, (1981) tries to reconcile the facts that there are often useful correlations between runoff and air temperature while net radiation is usually the major source of ablation energy. Although net radiation is generally the largest energy source, the ablation rate or runoff is often moderately well correlated with temperature and poorly correlated with net radiation. The average correlation between runoff and temperature in four studied glaciers in the Canadian Arctic is only 0.73±0.11 which corresponds to an "explanation" of slightly more than half of the variance of daily ablation.

Analysis of the meteorological and hydrological datasets forms the main part of this research: correlation, lag cross correlations and regression analyses are employed to assess the seasonal evolution of relationships between temperature, net radiation and discharge. The raw data were plotted in order to reveal stages in the evolution of the system. There was a high serial autocorrelation in the residuals so the data were first differenced $(t+1)-t$ i.e. change over three hours and seasonally differenced $(t+8)-t$ i.e. change from day to day. This provided residual values which physically represent the variability within the data and this too was analysed. Differencing allows the rate of change of air temperature to be related to the rate of change of glacial discharge. First differenced data, did not remove the daily trends and the correlation between the two variables was almost negligible. Detrended temperature values decrease autocorrelation and cross correlation in regression analysis compared to raw temperature data. The use of a detrended data series offers a way of eliminating seasonality in air temperature and net radiation records but the strength of the relationships between discharge, temperature and net radiation change with the differencing factor applied to the data.

Whilst the bed topography has remained stable for a number of years, the recession of the snowpack, development of supraglacial lakes and evolution of surface drainage channels will almost always be slightly different from year to year. Positive lag times indicate that air temperature is leading discharge. A large lag at the end of the season suggests that over the melt season, the drainage system has taken a long time to evolve in order to effectively and quickly transport water to the ice margin and the monitoring station; water is still slow to reach the ice margin. Negative lags indicate that discharge leads air temperature, thereby invalidating a casual relationship between the two and it implies that there is another variable controlling at least some of the discharge recorded.

Auto correlation clearly exists in all data sets implying that all variables are not only influencing the others but they are also influenced by past values of itself. This is probably because once melting begins in May, water is likely to remain in transit even if air temperature and net radiation drop. This method, based on high frequency systematic analysis can be used to describe changes in glacial drainage networks caused by snow and ice meltwater processes (Jobard and Dzikowski, 2006).

3. Results and Analysis

This chapter reports the results of the statistical analysis described in chapter 2. The first section presents preliminary findings based on the discharge and air temperature data, spanning odd years 1985 to 2007. The second section reports on the relationship between net radiation, discharge and air temperature between 1999 and 2005. The observations are divided into subsections to enable each of the research aims to be addressed in turn.

3.1 Raw Melt Season Data

The raw data were plotted on a time series graph to reveal stages in the evolution of the drainage system and to see if there were any exceptional meteorological or discharge events (figure. 3.1). In the discharge time series it is immediately obvious that in 2001, 2003 and 2005 there were very high discharge events in August and early-September. Because of these large discharge events the data was plotted on different axes to enhance the visible patterns within the data (figure. 3.2). Two distinct discharge regimes were recognised from the discharge data; the beginning and end of the melt season is characterised by consistently low signals whereas high and more variable signals dominated the middle of the season. This contrasts with the work of Jobard and Dzikowski, (2006) where the daily discharge regimes were more stable in the middle of the melt season than at the beginning or end.

The air temperature shows daily oscillations but on the whole rises and falls over the duration of the summer melt season and after mid-June air temperatures mostly exceed 0°C. The trend in air temperature shows a rise from predominantly negative temperatures in May to predominantly positive figures by then end of June for all years before falling again at the end of August. There is much more disparity between the years in May and June and again in September than in July and August when they are more constant. Mean summer temperatures (May-September) ranged from 1.61°C in 1999 and 4.93°C in 2007. All of the melt seasons were punctuated by several episodes of below-freezing temperatures; however, 1999 was particularly cold during the last two weeks of May.

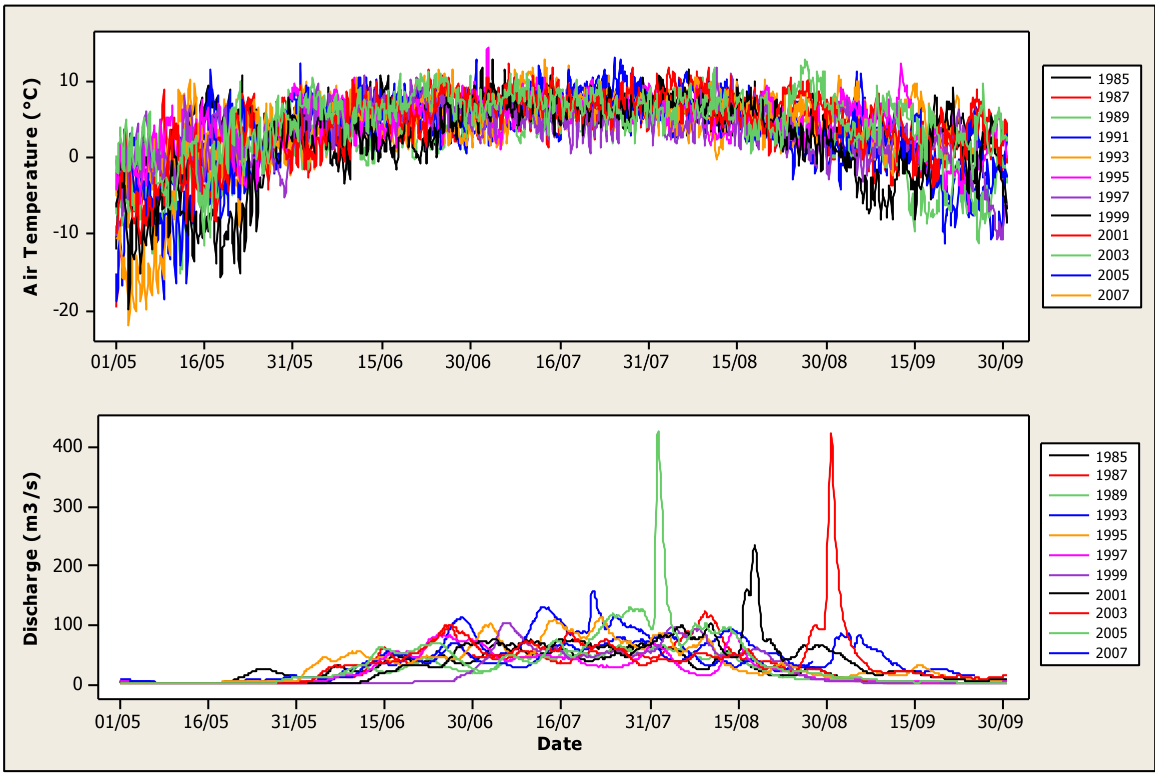


Figure 3.1. Air temperature and discharge time series from station 437.

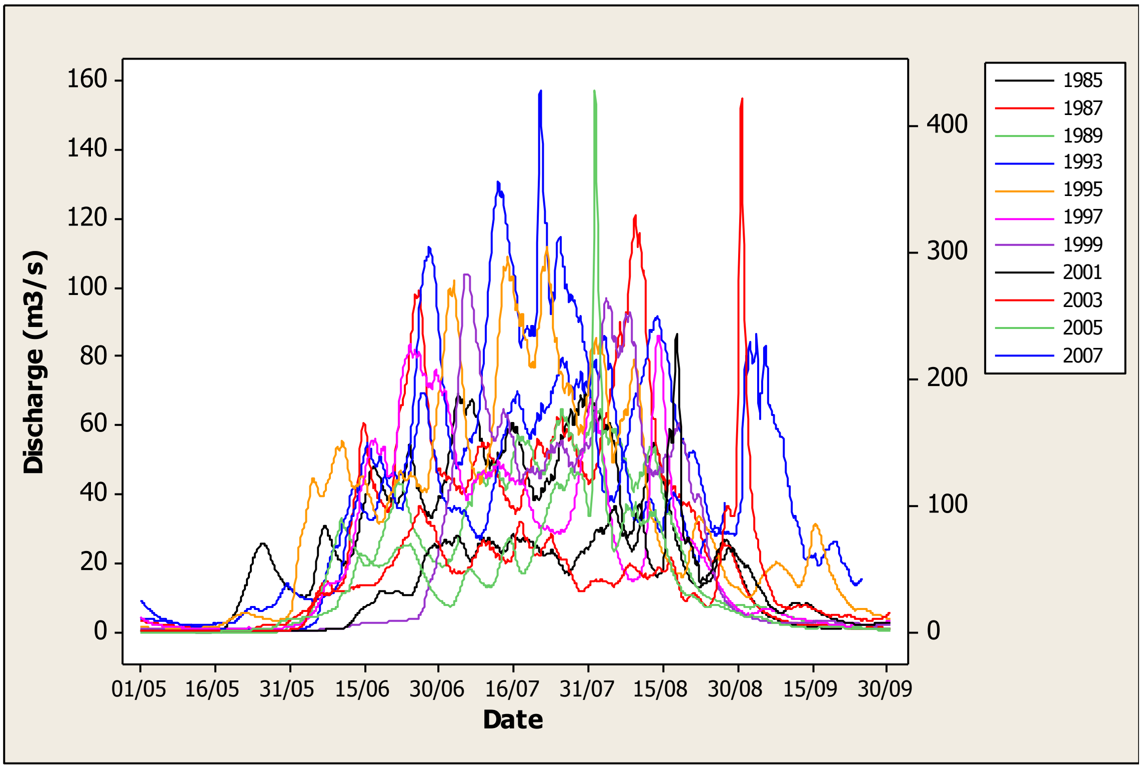


Figure 3.2. Discharge times series from station 437. Data from years 2001, 2003 and 2005 have been plotted on the secondary axis (right) to enhance trends within the other years.

3.2 Average Melt Season Statistics

The averages (1985-2007) for each data point were calculated and analysed to show the general trends in seasonal evolution and the relationship between discharge and air temperature. A time series plot was computed (figure. 3.3) which shows the rise and fall in air temperature over the melt season, May – September. Although air temperatures begin to rise in early-May, discharge does not start to respond and rise significantly until early- June. In contrast, by mid-August, discharge begins to fall rapidly whilst air temperatures take longer and by the end of September have not fallen to the lows that were recorded in May and earlier. This suggests that air temperatures are no longer influencing the ice melt and discharge. Figure 3.3, shows that there is much more diurnal variation in the discharge record between early-July and mid-August than for the rest of the melt season and this will become clearer when the data is split and analysed in monthly sections. The two anomalous discharge events, late-July and early-September have been heavily influenced by the extreme events that took place in 2003 and 2005.

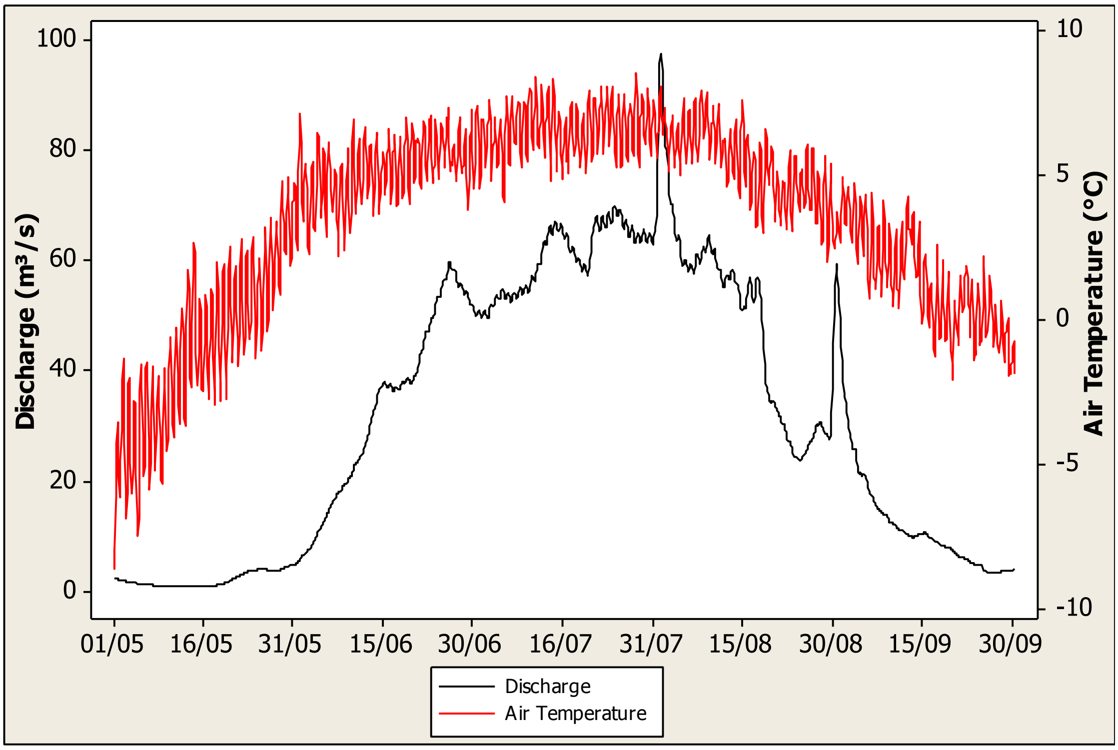


Figure 3.3 Time series showing the average of all sampled years for each data point.

Table 3.1 shows the deviation between the two variables. There is much more variation between the discharge data with the high maximum value of 97.57m³/s and a mean of only 31.43m³/s hence why standard deviation is much greater for discharge than for air temperature. The low standard deviation for air temperature may be accounting for the diurnal variations although this seems unlikely to be the sole cause of the deviation. The Pearson correlation value between the data is 0.808 which is extremely high given the spread of discharge data shown in both figure 3.1 and table 3.1. Furthermore the scatter plot in figure 3.4 implies that it is not until temperatures reach around -2.5°C that melting starts to occur. Between 0°C and 7.5°C the discharge tends to increase with temperature but the data is significantly spread around the linear regression line (in blue). This relationship may be true at the beginning of the melt season but towards the end of the season, temperatures remain fairly steady whilst discharge falls dramatically and rapidly.

	Discharge (m³/s)	Air Temperature (°C)
Minimum	0.79	-8.63
Maximum	97.57	8.57
Mean	**31.43**	**3.51**
Standard Deviation	25.05	3.33

Table 3.1 Summary statistics computed from the averaged data.

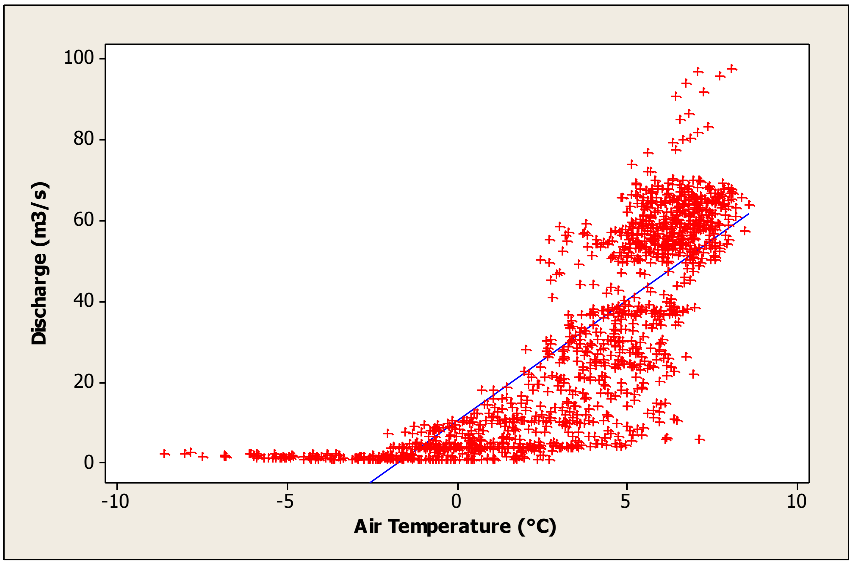


Figure 3.4. Scatter plot of average melt season air temperatures and discharge readings over the entire study period, 1985-2007.

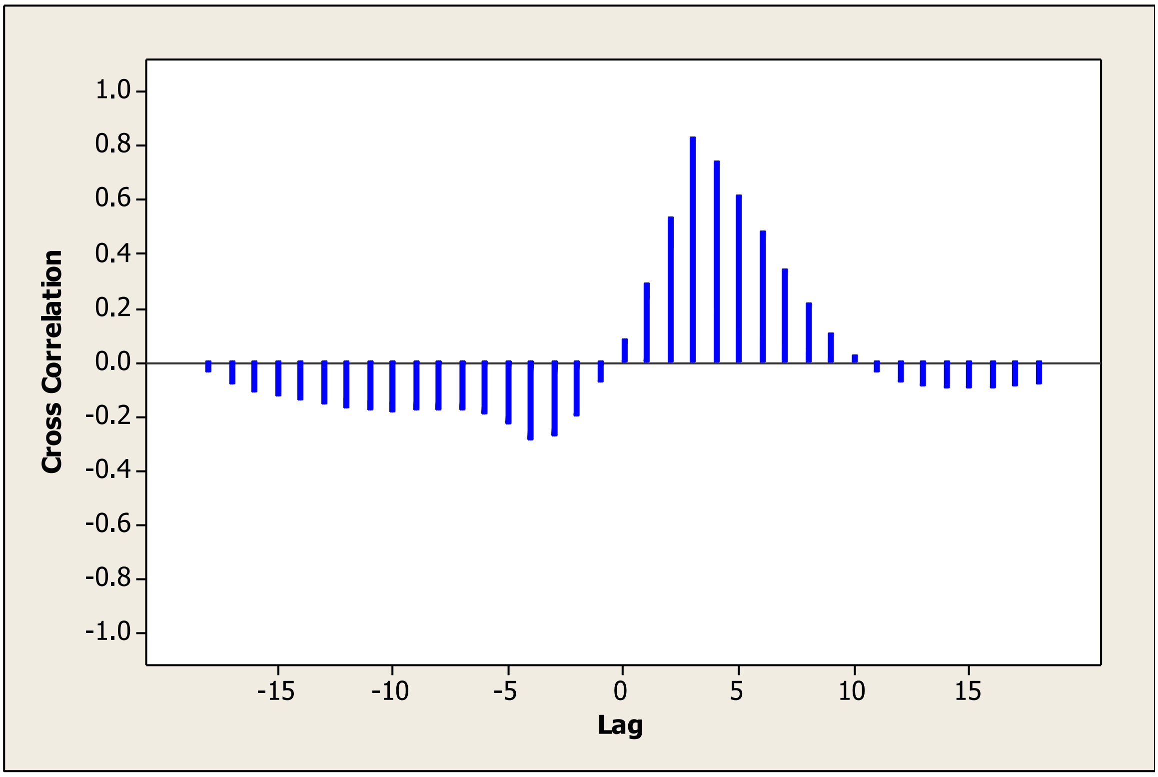


Figure 3.5 Cross correlation function of the residuals. Correlation coefficients (vertical bars) between means of three hourly discharges (dependent variable) and air temperature at station 437.

This very simple cross correlation surprisingly shows very good correlation between the residuals which is similar to the Pearson correlation value of 0.808. The correlations are all negative before a lag of 0 which means that air temperature can account for a lot of the discharge that is measured at later lags. Over the study period, the average, melt season lag peaks at “3”, this means that a peak discharge occurs 9 hours after a peak temperature before it starts to fall again. After 33 hours, previous air temperatures have stopped influencing the current discharge.

In summary, over the entire study period discharge is highly correlated with air temperature as shown by the Pearson correlation coefficient and the cross correlation (figure 3.5). This seems to be an unlikely scenario however as visually the early and late season correlation between the variables is poor with air temperatures rising sharply and continually at the beginning of the season for two weeks before discharge starts to increase.

3.3 Monthly Average Data for 1985-2007

Figure 3.6 shows the average time series for each month over the melt season. Each data point at three hourly intervals has been averaged and only the odd years have been included. The plots have been separated into monthly periods to better show the trends and relationships between discharge and meteorology. Immediately visible is the diurnal fluctuation in air temperatures.

In **May,** there is a rising trend in air temperature from negative to positive and whilst discharge does not show distinctive diurnal patterns, after May 16th it begins to rise. When temperatures fall on May 15th discharge does not respond however, when the peak temperature falls on May 25th, it takes 36hours for the runoff to respond reaching a low value on the 28th before steadily rising again. In **June** there is not as much variation of air temperature over the course of the month (between 2.3°C and 7.2°C), although there is a very slight increasing trend but this is punctuated by a number of cooler peak temperatures for example June 27th when the peak temperature is less than 6°C compared to a temperature of over 6.5°C in the previous four days. Comparatively, there are larger changes in the discharge data. Although diurnal variations are not clearly visible, after June 21st the data isn't smooth suggesting that this may be a transition period from air temperature having little effect on runoff to it playing a much more significant role. In **July** there is a distinct shift in the discharge record and there are visible diurnal variations in the data. The peaks in discharge do however lag behind the air temperature data as would be expected whilst the runoff passes through the hydrological system before reaching the monitoring station at Lake 187. There is however change of only a couple of degrees within the air temperature record whilst there is a much larger variation within the discharge record that cannot be accounted for by diurnal variations suggesting that in July, air temperature is not the only variable that is controlling glacial discharge. In **August,** there is still diurnal fluctuation within the discharge data but the general trend shows the discharge to be falling along with the air temperatures. After August 18th however the discharge signal becomes much smoother, continuing to fall whilst the average daily temperature remains fairly steady. **September**'s time series is almost identical to that of May but in reverse. Runoff falls to almost 0m^3/s by September 24th although air temperatures largely remain above 0°C.

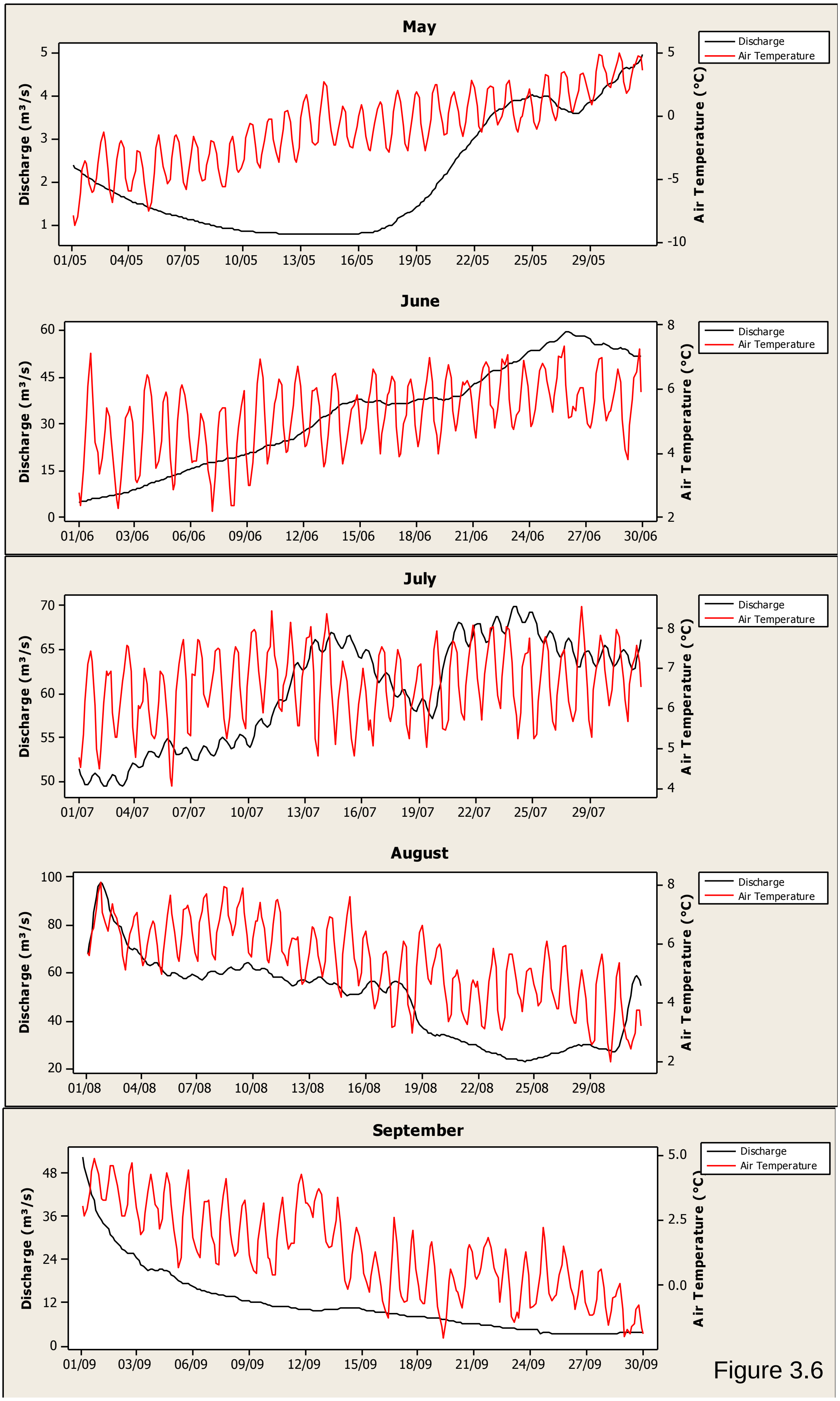
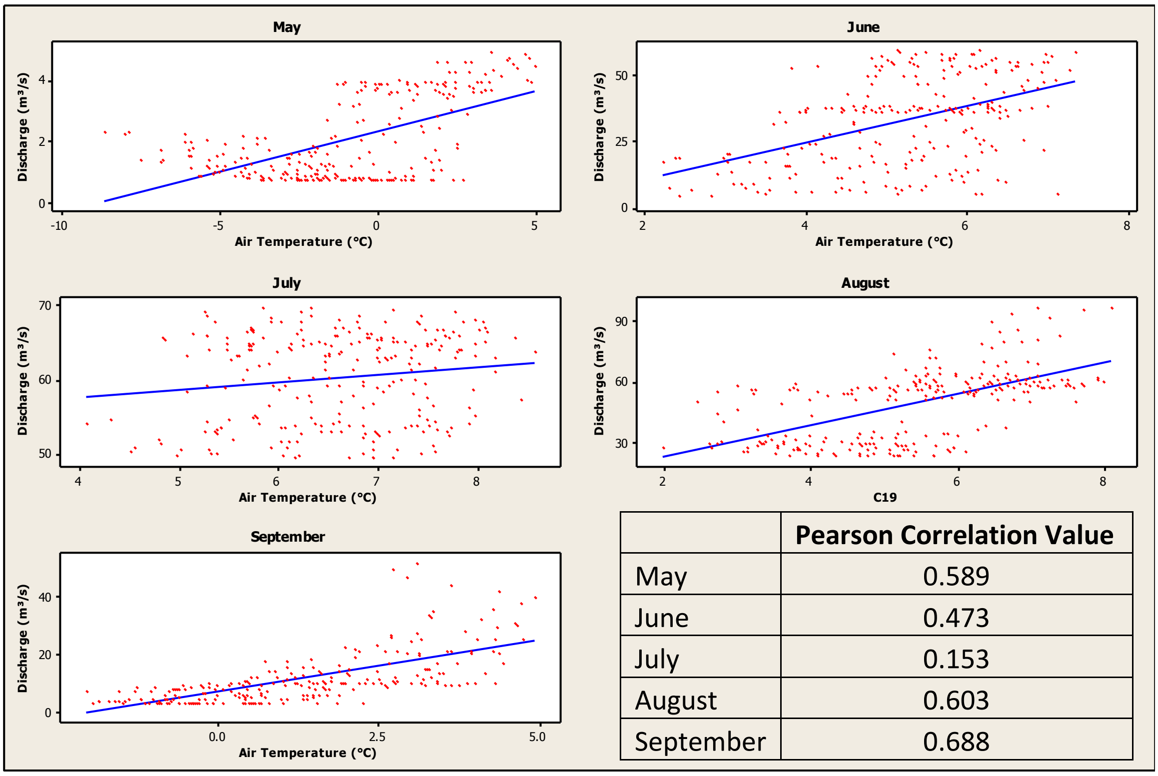

May
June
July
August
September
Discharge
Air Temperature
Discharge (m³/s)
Air Temperature (°C)
01/05
04/05
07/05
10/05
13/05
16/05
19/05
22/05
25/05
29/05
01/06
03/06
06/06
09/06
12/06
15/06
18/06
21/06
24/06
27/06
30/06
01/07
04/07
07/07
10/07
13/07
16/07
19/07
22/07
25/07
29/07
01/08
04/08
07/08
10/08
13/08
16/08
19/08
22/08
25/08
29/08
01/09
03/09
06/09
09/09
12/09
15/09
18/09
21/09
24/09
27/09
30/09

Figure 3.6

Discharge (m³/s)	May	June	July	August	September
Minimum	0.79	5.08	49.50	23.54	3.38
Maximum	4.96	59.56	69.97	97.57	52.31
Mean	2.09	32.93	60.50	49.18	11.81
Standard Deviation	1.31	16.61	6.03	17.53	9.17
Air Temperature (°C)					
	May	June	July	August	September
Minimum	-8.63	2.22	4.07	1.99	-2.05
Maximum	4.96	7.33	8.57	8.07	4.91
Mean	-0.96	5.20	6.59	5.38	1.28
Standard Deviation	2.91	1.13	0.90	1.34	1.71

Table 3.2 Summary statistics of monthly averaged data, 1986 – 2007. (See appendix 2 for more detail)



	Pearson Correlation Value
May	0.589
June	0.473
July	0.153
August	0.603
September	0.688

Figure 3.7. Scatter plots of average monthly melt season air temperatures and discharge readings over the entire study period, 1985-2007. Table in the bottom right shows the Pearson correlation values between the data.

The scatter plots in figure 3.7 show that the best correlation between air temperatures and discharge is in September (0.688) even though the diurnal structure in the discharge signal is not present. In May it is clearer that air temperature is not correlated well with discharge as there is very little discharge occurring despite the rising temperatures. This may be because net radiation in the early melt season is low due to the albedo effect of the snow. Similar patterns are visible throughout all years and this could be explained by the availability of large amounts of snow for melting when the air temperature rises in May and the decay of the accumulation area ratio after June. This will be explored further later in the section.

In summary, it is shown that runoff increased in May and decreased in September. Table, 3.2 confirms this as the average monthly discharge rises dramatically from 2.09m^3/s in May to 32.93m^3/s in June and continues to rise in July before falling in August and September from 49.18m^3/s to 11.81m^3/s. The average monthly discharge for September is still 11.81m^3/s, although by 24 September, discharge is 0m^3/s. This is also the case for air temperatures as the mean temperature in September is still positive at 1.28°C and only on 30 September does temperature stay below 0°C for the whole daily cycle. The air temperature data shows less variation around the mean in all months especially in July when temperatures are highest causing smaller diurnal variations.

3.3. Yearly Melt Season Analysis

The data was divided into yearly melt season sections and analysed accordingly to show the inter-annual trend between 1985 and 2007. Many of the analyses in this section were not carried out on the 1991 data as there was no discharge data recorded for that year.

The summary statistics were computed for each odd year, May to September and are represented in table 3.4. Of particular interest is the significant fall in average air temperature in 1999 and the subsequent rise by 2001. These values were then plotted to give a visual representation of the changing trends in air temperatures and discharge readings. In figure 3.5 although the data is not uniform and neatly fitting around a trend line, it is immediately obvious that whilst the mean and maximum values for air temperature vary little, the discharge data shows much more disparity. With the exception of 1989, 1997 and 1999 the average seasonal discharge is increasing. Perhaps oddly, in 2007 when the maximum seasonal discharge falls dramatically from 427 m^3/s to 157 m^3/s, the average discharge increases from 37.30m^3/s to 47.90m^3/s – the highest mean value of the study period. In 1995, the minimum and maximum air temperatures were elevated and the maximum discharge measurement for that year was also elevated. However there is no statistical evidence that elevated air temperatures caused the increase in maximum discharge. Table 3.3 shows that the seasonal changes were not regular. Over the study period the average seasonal temperature rose 0.26°C whilst the average seasonal discharge rose by 9.49 m^3/s. The rise in air temperature is of special interest when compared to the IPCC Fourth Assessment Report (2007). The IPCC report states that over the last 100 years global temperatures have risen by 0.74°C. This study has reported a rise of 0.26°C in 22 years which is 0.1°C higher than the global average for the equivalent time frame.

	1985	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Temperature (°C)		-0.98	-1.82	0.78	0.63	1.05	-1.09	-1.63	2.66	0.61	-1.13	1.18
Discharge (m^3/s)		3.03	-7.73			0.61	-9.47	-0.76	13.8	1.61	-1.36	9.79

Table 3.3 The change in seasonal mean air temperature and discharge compared to the previous year studied.

	Air Temperature (°C)	Discharge (m³/s)		Air Temperature (°C)	Discharge (m³/s)
1985	-12.0 10.7 **4.4** 3.2	0.01 69.70 **25.99** 21.92	**1997**	-10.8 11.6 **3.2** 3.6	0.65 86.20 **24.03** 24.37
1987	-19.5 11.7 **3.7** 4.1	0.70 121.00 **29.02** 28.60	**1999**	-19.9 12.7 **1.6** 5.7	0.14 104.00 **23.27** 29.49
1989	-15.1 10.7 **1.9** 4.8	0.07 64.80 **21.29** 20.94	**2001**	-11.3 12.3 **4.3** 2.2	0.48 235.00 **37.05** 36.09
1991	-18.4 12.6 **2.7** 4.9		**2003**	-11.4 12.7 **4.9** 3.8	0.27 421.00 **38.66** 42.30
1993	-21.8 10.7 **3.3** 5.3	1.95 86.60 **34.69** 24.04	**2005**	-18.8 12.9 **3.8** 4.8	0.03 427.00 **37.30** 47.71
1995	-7.0 14.2 **4.3** 3.3	0.79 112.00 **35.30** 29.95	**2007**	-9.2 12.6 **4.9** 4.1	0.50 157.00 **47.09** 39.11

Table 3.4 Summary statistics for discharge and air temperature for each odd year between 1985 and 2007. Values represented are the minimum (upper value) maximum (second value) mean (in bold) and standard deviation (lower value).

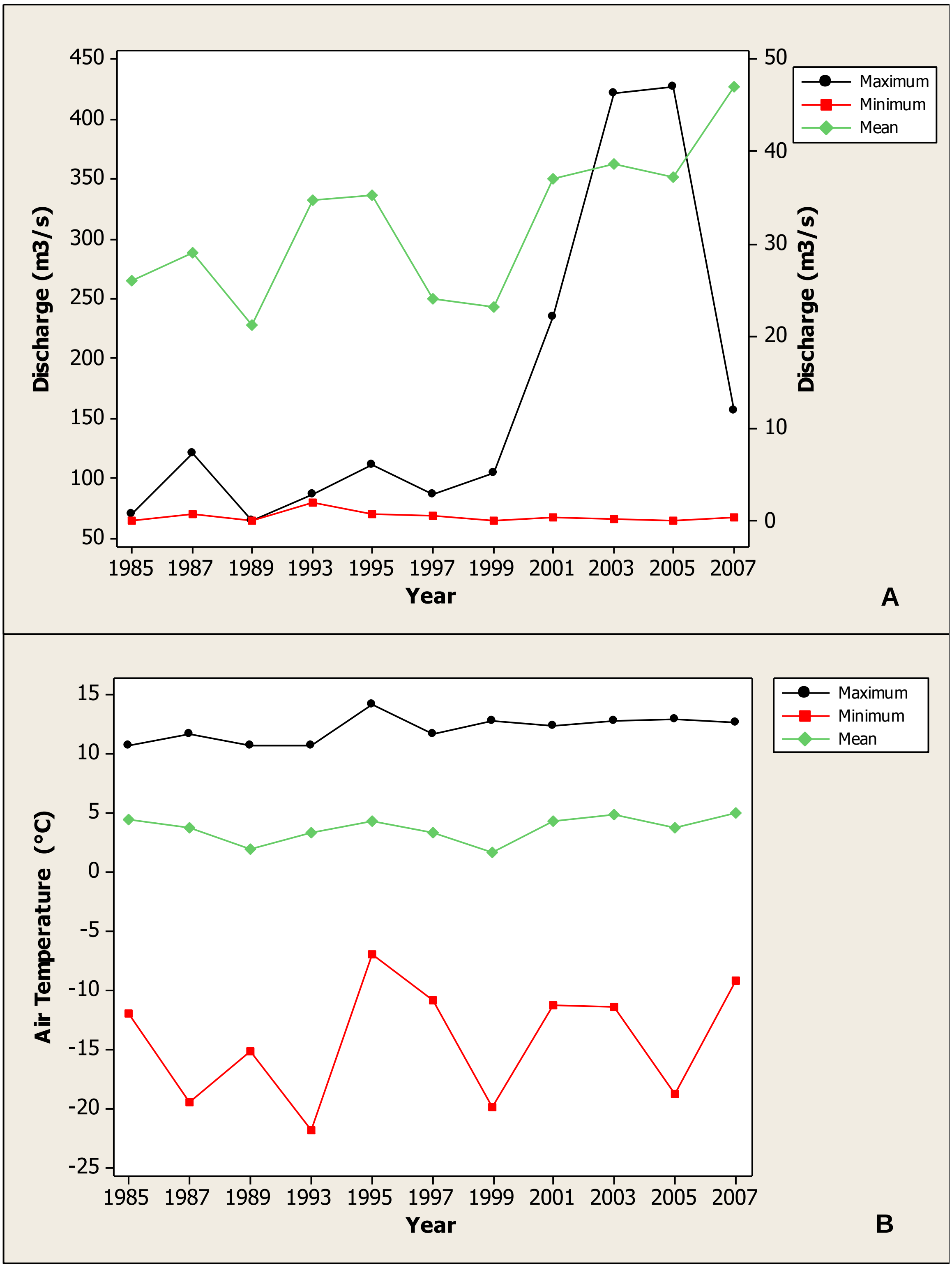


Figure 3.8 Represents the maximum, minimum and mean data in table 3.3. **A** presents the discharge data. The maximum values are plotted on the primary axis and the minimum and mean values are plotted on the secondary axis. **B** presents air temperature data.

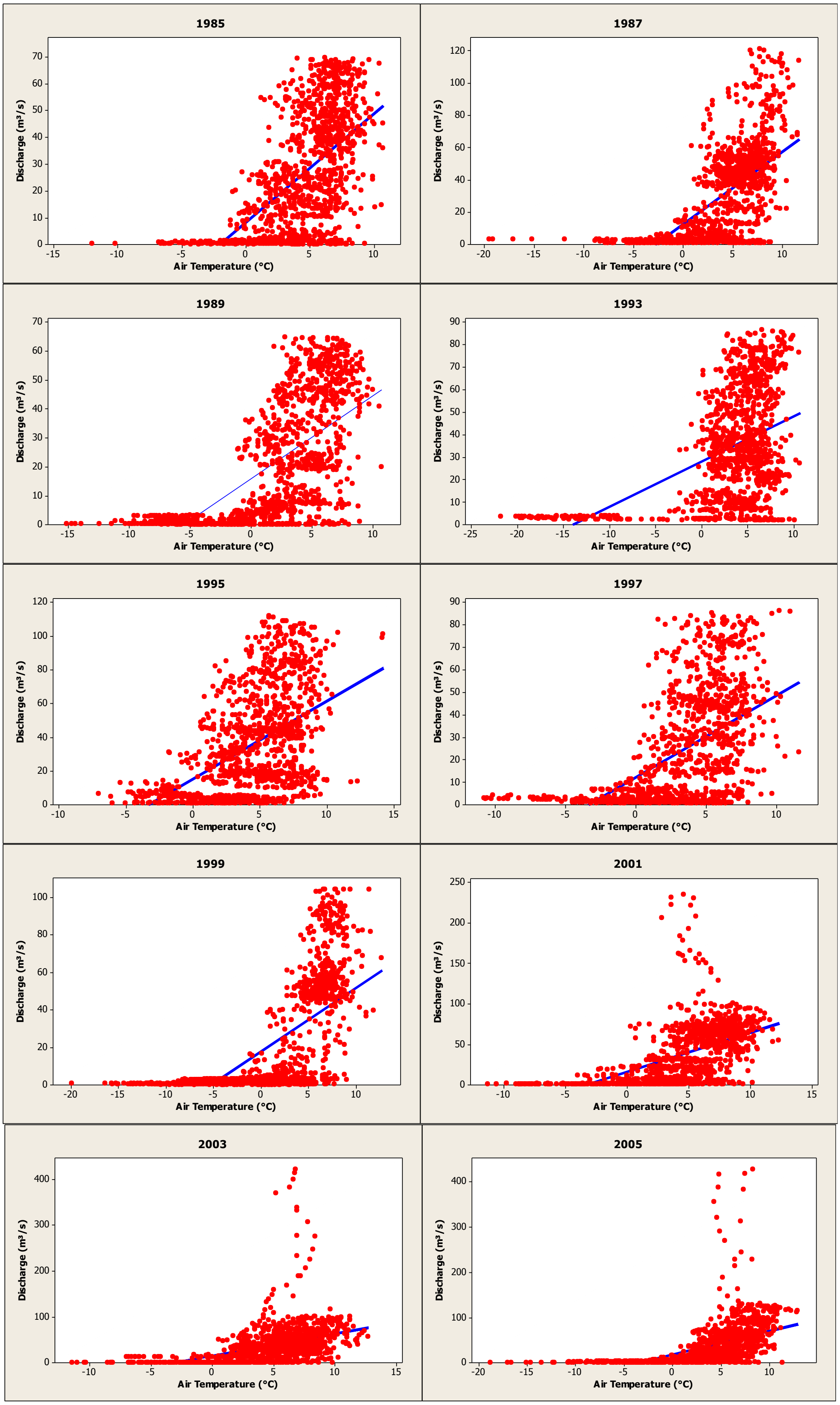


Figure 3.9 Contd.

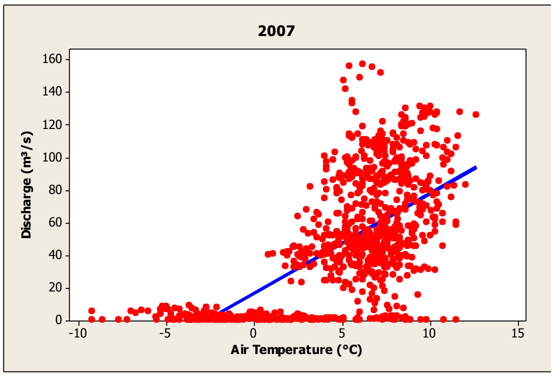


Figure 3.9 Contd.

	Pearson Correlation Coefficient
1985	0.596
1987	0.648
1989	0.657
1991	-
1993	0.445
1995	0.509
1997	0.542
1999	0.662
2001	0.568
2003	0.429
2005	0.515
2007	0.637

Table 3.5

Figure 3.9 Scatter graphs representing the summer season (May to September) for each year used in this study.

Table 3.5 Correlation between air temperature and discharge for each of the seasonal scatter graphs in figure 3.6.

All of the scatter graphs are very similar until 2001, when the three large drainage events are having a significant impact upon the scatter around the trend line in the graphs for 2001, 2003 and 2005. The scatter in 2007 is different to the others and this is to be expected due to the high mean discharge despite there not being an anomalous maximum discharge as there was in 2001, 2003 and 2005. This demonstrates that the discharge values recorded in 2007 were consistently higher than all other years as well as being one of the highest three seasons for correlation between air temperature and discharge. The other two years with better correlation between the variables were 1987 and 1989 which is notable because there was an upward trend between these years for mean discharge but a downward trend for mean air temperatures. Because of these trends it might be hypothesised that correlation would be less in 1989 than 1987 but in reality table 3.5 shows that it was marginally higher.

With reference to the individual yearly time series plots in appendix 1 the seasonal cross correlation plots in appendix 3 (combined in figure 3.6), and to table 3.5, it is clear that the lag between seasonal meteorological forcing on discharge varies from season to season and this could be attributed to the different evolution of the drainage network from year to year.

	No differencing		**Seasonally differenced**	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.647	78	0.153	42
1987	0.676	33	0.156	30
1989	0.678	57	-0.155	-12
1991				
1993	0.517	99	0.120	75
1995	0.621	57	0.269	36
1997	0.580	57	0.130	57
1999	0.678	57	0.137	27
2001	0.630	57	-0.105	-84
2003	0.569	102	0.139	36
2005	0.543	33	0.090	-12
2007	0.721	87	0.187	69

Table 3.6. Lag cross-correlation analysis of seasonal air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

Table 3.6 shows markedly different maximum correlation values for the raw data and for the seasonally differenced data. Once the diurnal trend has been removed, the correlation drops dramatically between the variables and in most cases the lag time also drops. For years 1989, 2001 and 2005, the data displays a maximum correlation at a negative lag. As it is assumed that discharge cannot lead air temperature, for these years, the relationship is deemed invalid. The lag times are much longer than expected however this may be due to the relatively gentle slope of the glacier enabling the melt water to move through the melt water conduits at a slower rate.

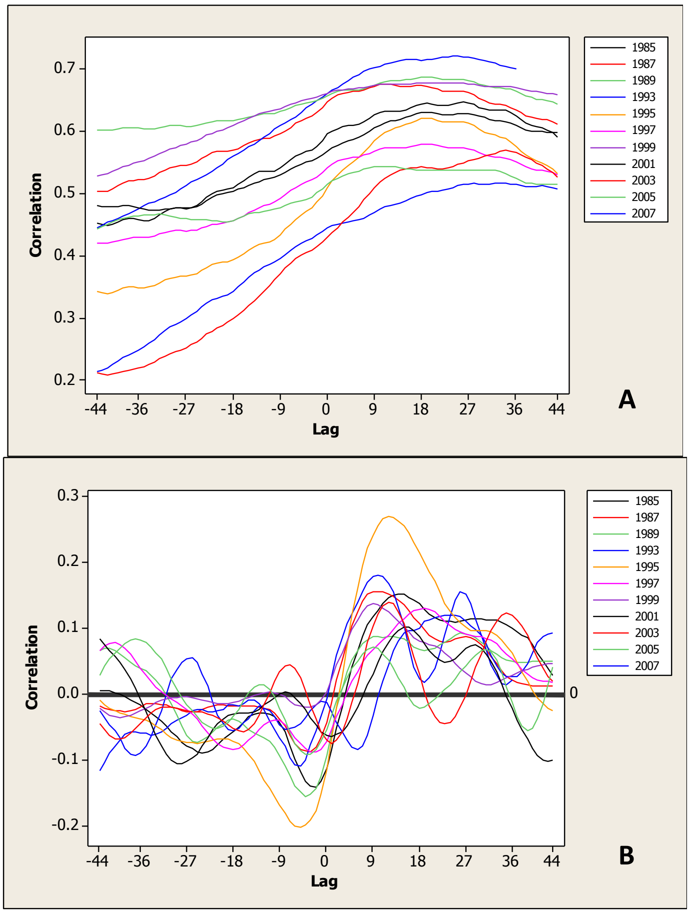


Figure 3.10. **A** cross correlation using raw data, **B** cross correlation plots using seasonally differenced data**.** (See appendix 3 for individual cross correlation plots)

The accumulated cross correlation plots in figure 3.10 show how the cross correlation between the raw data is variable. At any particular lag period, each year calculates a very different correlation value. In plot **A** the two years with suspected diurnal variation in the residuals are 1987 and 1989 although most years show some degree of oscillation. These years were noted previously due to the high correlations between the air temperatures and discharge values. In plot **B**, most of the years display consistent positive correlations for the positive lags and negative correlations for negative lags which would be expected if air temperature were to be the only control over discharge. 1995, has a much higher correlation than all the other years at a lag of 24 hours so it can be assumed that in 1995, at the seasonal scale the influence of air temperature over discharge was stronger than other years and had most impact 24hours after any particular air temperature was recorded.

Autocorrelation was also calculated for both air temperature and discharge at the seasonal timescale. In figure 3.11, plots A and C depict the raw data collected at station 437 on a seasonal basis. Within A, the discharge data, 2003 stands out above the other years as the correlation between the residuals drops much faster than any other year. The correlation is less than any other data set before 8, or 24 hours has passed. This suggests that during 2003 discharge was not very well correlated with other values of discharge. During other seasons residual discharge values are still influencing runoff over 9 days later. The raw air temperature (C) demonstrates that there is a significant seasonal trend due to the diurnal nature of air temperatures. The peaks within the autocorrelation residuals do however occur at 24 hour intervals so the diurnal pattern is very important in predicting the temperatures at the same time over the following days.

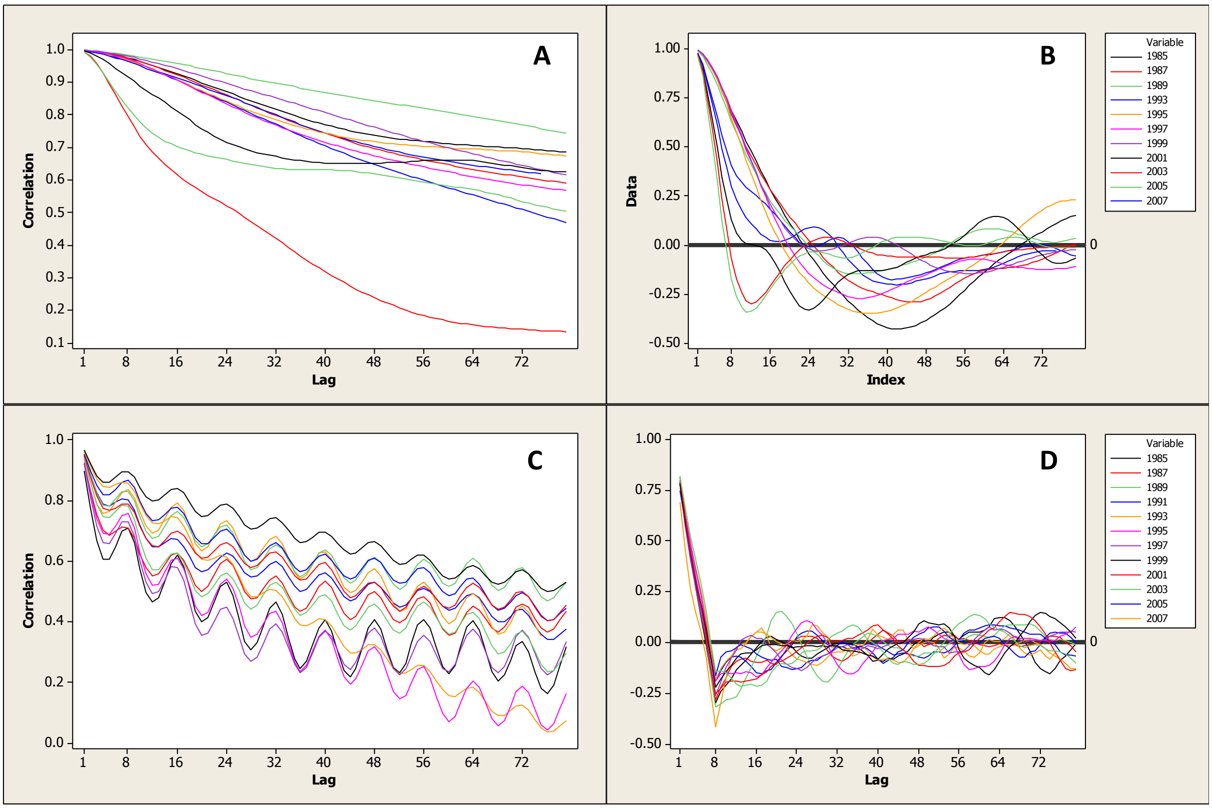


Figure 3.11 Autocorrelation plots for each year studied. **A** Raw discharge autocorrelation. **B** Seasonally differenced discharge autocorrelation. **C** Raw air temperature autocorrelation. **D** Seasonally differenced air temperature autocorrelation.

Plots B and D were made using seasonally differenced data to try and remove the seasonal trend that is seen especially in the air temperature data. The correlation within the discharge data (B) falls quickly almost always reaching 0 within 72 hours and in the case of 2003 and 2005, the correlation between the residuals drops to 0 within 24 hours. The air temperature data (D) shows a much clearer trend with all years falling to 0 after exactly 24hours and mostly becoming significantly negative before rising again after the 24hour period. Each year shows a different trend within the residuals but the correlations remain low and between 0.1 and -0.25.

Referring back to the observations regarding Figure 3.6 and the visible diurnal fluctuations within the discharge record as well as the air temperature record, the yearly time series' were analysed for similar patterns. The transition from an irregular discharge pattern to one with clear diurnal variations happens over the course of every season. Figure 3.12 and table 3.7 represents the time when discharge has a diurnal fluctuation within the record. The onset and cessation of diurnal cycling varies from year to year and the duration reflects this with no trend between the years. Surprisingly, due to the extreme discharge events in 2001, 2003 and 2005 it might be presumed that there was excessive melting that year and that the diurnal pattern would last longest during these years but in the case of 2005, the duration was the shortest at 25 days.

	Start	**Finish**	**Duration (Days)**
1985	19-Jun	06-Aug	49
1987	01-Jul	22-Aug	53
1989	16-Jul	13-Aug	29
1991			
1993	04-Jul	10-Sep	69
1995	10-Jun	07-Aug	59
1997	16-Jun	28-Jul	43
1999	13-Jul	19-Aug	38
2001	29-Jun	29-Aug	62
2003	12-Jun	16-Aug	66
2005	20-Jul	16-Aug	25
2007	05-Jul	21-Aug	48

Table 3.7. Onset and cessation of diurnal cycling within the discharge data and the number of days that it lasts for.

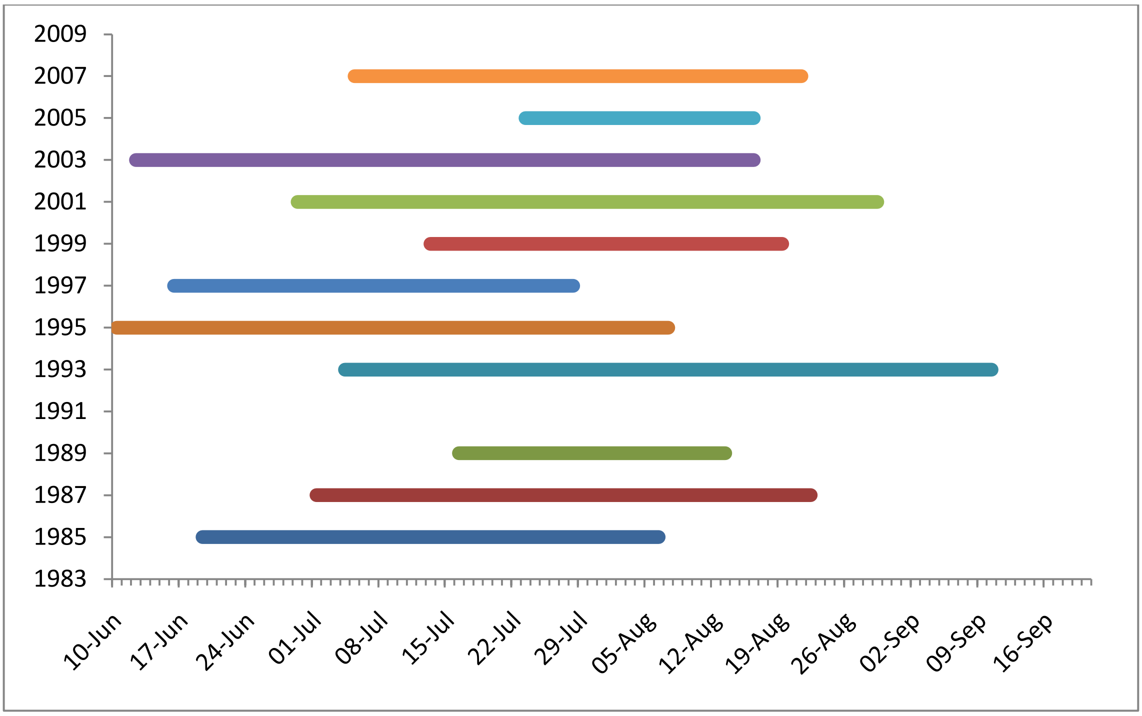


Figure 3.12 Graphical representations of the data within table 3.6, showing the seasonal extent of diurnal cycling within the discharge data.

Table 3.6 and figure 3.8 show the durations of diurnal cycling within the discharge record recorded at station 437 and whilst this is significant it does not take into account the actual onset and cessation of melting or the magnitude of diurnal oscillations with respect to other years.

In summary, with the exception of 1989, 1997 and 1999 the mean discharge is rising. Air temperature is also rising but it is not as dramatic or unpredictable as the trend in discharge as seen in figure 3.5. The rise of 0.26°C over the study period is 0.1°C higher than the global average change for the same time frame which suggests that Greenland is responding faster to global warming than other regions. The IPCC report (2007) is however an average and so there would be areas with a greater increase, Greenland it would appear, is one of them. Increases in air temperatures on the seasonal scale are not directly comparable to changes in seasonal discharge. In the case of years 1987 and 1989 one variable (air temperature) is falling, whilst the other variable (discharge) is rising. Relationships may prove to be better correlated between the variables at the monthly scale when similar statistical tests are carried out for each month in each year used in this study.

3.4 Monthly Analysis

The data was divided into monthly sections and analysed accordingly to show the trend in each month between seasons 1985 and 2007. Many of the analyses in this section were not carried out on the 1991 data as there was no discharge data recorded for that year.

The descriptive statistics have been calculated for each year by month (May – September) and are on pp51 to pp53. They will be referred to within the following analysis of each month. Monthly scatter graphs for each year were also plotted. However due to the large number and variable correlations a summary table was produced (figure 3.8), this will also be referred to within the monthly analysis and the scatter graphs themselves are held within appendix 4.

	May	June	July	August	September
1985	0.256	0.245	0.070	0.231	0.095
1987	**-0.103**	0.408	0.149	0.672	**-0.035**
1989	0.170	**-0.116**	0.067	0.576	0.665
1991	-	-	-	-	-
1993	0.285	0.059	0.238	0.239	0.240
1995	0.004	**-0.246**	0.166	0.324	0.219
1997	**-0.523**	0.335	**-0.029**	0.372	0.247
1999	**-0.292**	0.499	0.101	0.766	0.065
2001	**-0.401**	0.540	**-0.175**	**-0.218**	0.232
2003	0.420	0.381	0.160	0.107	0.268
2005	0.377	0.306	0.490	0.358	0.566
2007	**-0.377**	0.114	0.168	0.203	-

Table 3.8. Pearson Correlation coefficient values. Negative correlations have been highlighted red.

3.4.1 May

With reference to table 3.9 and figure 3.13, the minimum (highest in 1999 with 2 m^3/s) and mean discharge values for May do not vary hugely over the years; the maximum values show a much more sporadic trend with values between $1.2 m^3/s$ and $25.9 m^3/s$. In 2005 when the maximum discharge rises sharply, to $10.4 m^3/s$ the mean value does not reflect this increase suggesting that the maximum value was attributed to a single discharge event rather than to an increasing trend. The air temperature values show much more disparity within the minimum values over the years than the maximum or means. The minimum values range between -21.8°C in 1993 and -6.1°C in 1995. This value fluctuates but never rises above 0 and had very little influence on the mean except during May 1999 when it drops to -6°C, suggesting that the month of May in 1999 was significantly colder than other years. The maximum air temperatures for May remain steady until 2005 when the maximum temperature is 11.3°C. This corresponds to the high discharge event that also occurs in 2005. By looking at the raw data, the dates of the peak air temperature and discharge in 2005 do not coincide. The highest discharge value was recorded on May 31st at 9pm and the peak air temperature on May 17$^{th\ at}$ 6 am.

The differences recorded in table 3.9 do not show an increasing or decreasing trend for either variable but the overall difference between 1985 and 2007 was a decrease of 2.9°C for air temperatures and a decrease of 9.3m³/s for runoff.

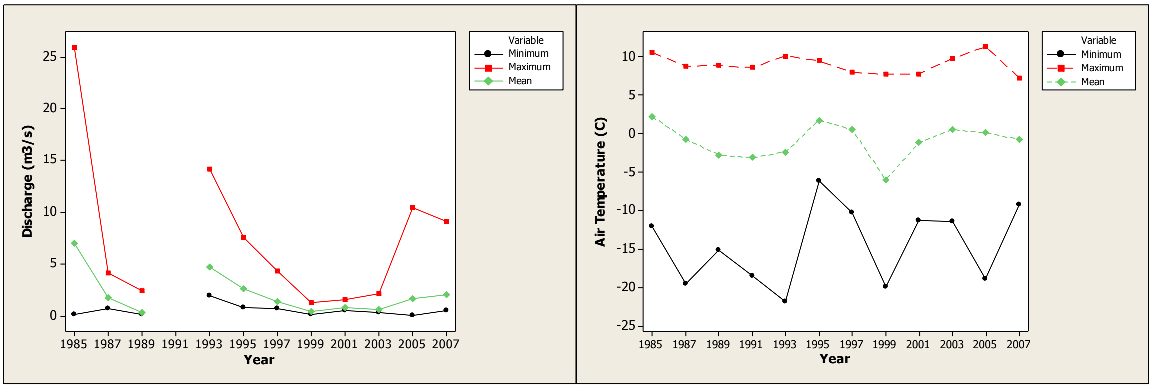


Figure 3.13 Minimum, maximum and mean values for the month of May for each odd year 1985-2007.There is a gap in the data as no discharge data was recorded at station 437 in 1991.

	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Temperature (°C)	-	-2.9	-2.1	-0.3	0.7	4.2	-1.2	-6.6	4.8	1.7	-0.4	-0.8
Discharge (m^3/s)	-	-5.2	-1.4	-	-	-2.1	-1.2	-1	0.4	-0.2	1	0.4

Table 3.9 Changes in monthly mean air temperature and discharge compared to the previous year sampled.

The scatter graphs in appendix 4 and the corresponding correlation values in table 3.10 show a weak correlation between air temperatures and discharge and in some cases, a negative correlation for the month of May (5 out of 11 years). The highest correlation between the two variables was in 2003 with a value of 0.42.

The autocorrelation and cross correlations functions were also calculated for the variables to analyse the lead/lag relationship between the two. Appendix 5 contains all of the accumulated graphs for these functions and the summary table (table 3.10) shows the changing lag over the sampled years.

	No differencing		**Seasonally differenced**	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.514	75	0.078	39
1987	0.180	72	0.191	66
1989	0.384	57	0.122	75
1991	-	-	-	-
1993	0.488	75	0.127	69
1995	0.194	75	0.182	75
1997	-0.523	0	-0.281	-3
1999	0.026	75	0.297	15
2001	-0.401	0	0.218	33
2003	0.531	33	0.249	39
2005	0.377	0	0.112	-21
2007	-0.377	0	-0.092	-42

Table 3.10 Lag cross-correlation analysis of May’s air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

The autocorrelation of air temperature shows a very clear seasonal trend. Once this seasonal trend had been removed, correlation for all years drops to 0 within 24 hours. After 24 hours, correlation remains low and sporadic. The discharge values are not as uniform in their relationship to each other as in May there is little if any diurnal variation. For many years, the residuals are correlated to previous values of discharge for over 72 hours. In the case of 1985, the relationship remains positive for up to 90 hours and in 1997, after reaching the lowest correlation value after 108 hours (4.5 days) the correlation begins to rise again.

The cross correlation analysis provides very low correlation values which in some cases are equal to the Pearson correlation coefficient values in table 3.8. The cross correlation carried out on the raw data shows a much better correlation between the residuals but exhibits interesting results. In 2005, the peak correlation occurs at a lag of 0hours. This seems unlikely in May as the glacial drainage system has had very little time to evolve and given the low slope angle of the ice, the possibility of peak discharge occurring at the same time as peak temperature is low. In 1997 almost the opposite happens, the peak correlation occurs at a lag of 0hours but the correlation is negative at -0.523. The seasonally differenced cross correlation, yields poor correlation values but visually displays a clearer relationship. For all years except 2005, the negative correlation values invalidate any relationship between air temperature and discharge at a negative lag. Discharge therefore is only controlled by air temperature after a particular air temperature value occurs and not the other way around for May. This "tipping point" temperature was suggested as -2.5°C in section 3.2.

3.4.2 June

Figure 3.14 shows that June 1999 followed the same pattern as May with a markedly reduced maximum and mean for both air temperature and discharge suggesting that the melt season did not start until much later in 1999. This also ties in with figure 3.12 which shows that the visible diurnal cycling within the discharge record did not start until comparatively late in the season, nor did it last very long. The same can also be said about 1989, where there was a reduction in mean air temperatures, runoff and length of the diurnal signal in the discharge record. The maximum discharge values show a trend to positive, rising from $54m^3/s$ in 1985 to $112m^3/s$ in 2007. The mean, however, shows less of a trend but still a positive one with an increase of $9.5m^3/s$ between 1985 and 2007. Minimum air temperatures are above 0°C for the years 1985, 1995, 1997, 2003 2005 and 2007. In 1989, the maximum and mean air temperatures drop but the minimum is rising, other than this the three values are equally spread for all other years suggesting that there is a good spread of data and very few extreme air temperature events within each individual year. The scatter graphs (appendix 4) and table 3.8 suggest that although the correlations are not high, they are less in most cases than those for May and there are only two negative values, 1989 and 1995. This is of interest as one might be led to believe that as the melt season continues that correlations would become stronger once the melting had begun.

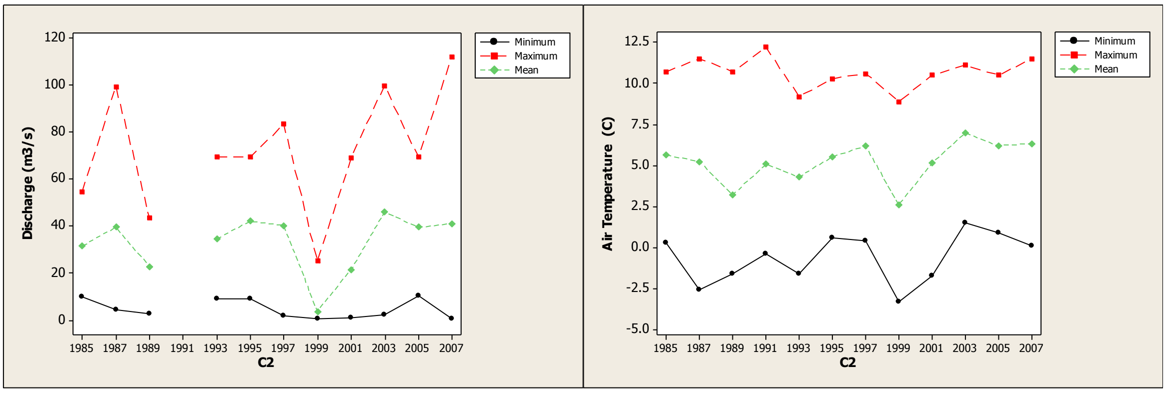


Figure 3.14 Minimum, maximum and mean values for the month of June for each odd year 1985-2007.There is a gap in the data as no discharge data was recorded at station 437 in 1991.

	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Temperature (°C)	-	-0.4	-2	2.9	-0.7	0.8	0.7	-3.6	2.6	1.8	-0.8	0.1
Discharge (m^3/s)	-	8	-16.7	-	-	7.5	-1.8	-36.7	18	24.3	-6.4	0.5

Table 3.11 Changes in monthly mean air temperature and discharge compared to the previous year sampled.

The autocorrelation residuals for both air temperature and discharge show varying degrees of seasonal repetition. For discharge the correlation remains above 0 for all years except 1989, 1995 and 2001 suggesting that in June the discharge values oscillate on a longer timescale than 7 days. The air temperature data oscillates between negative and positive values after first dropping below 0 at a lag of 9hours for years 1987, 1997, 1999 and 2001. After 24 hours, all years apart from 2003, 2005 and 2007 are below 0. This suggests that for June in the last three years studied that air temperature had an influence over itself for longer during the month of June. Once the data has been differenced, the discharge data shows different time lapses for the residuals to no longer have an effect on itself. For the majority of sampled years, the correlation reaches 0 at a lag of between 48hrs and 60 hrs. The longest lag is for 2001 with 153 hrs (6days 7 hours).

The cross correlation plots in appendix 5 and the maximum lags in table 3.12, although not uniform in their trends show a recurring lag for both the non-differenced and seasonally-differenced data. For the raw data, a lag of 54 hours is repeated for 5 of the 11 years analysed and for the differenced data 4 of the 11 years have a peak lag time of 39 hours with another 2 years that have peak lags within 6 hours of this.

	No differencing		**Seasonally differenced**	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.464	54	0.229	39
1987	0.582	48	0.278	39
1989	0.220	75	0.149	75
1991	-	-	-	-
1993	0.454	75	0.254	39
1995	0.200	54	0.192	66
1997	0.443	54	0.222	51
1999	0.417	24	0.136	48
2001	-0.401	0	0.218	33
2003	0.507	54	0.306	21
2005	0.461	39	0.404	39
2007	0.288	54	0.149	33

Table 3.12.Lag cross-correlation analysis of June's air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

3.4.3 July

The basic statistics for July show a significant rise in discharge in 2007 for minimum, mean and maximum. This is in line with an increase in mean air temperatures for 2007 as well, although the maximum temperature in July is less than the value for 2005. The correlations taken from the scatter graphs in table 3.8 show in general the lowest correlations of all months although the cross correlation table has relatively high values and much shorter lag times than those recorded for June. For most years the raw data has a lag of either 33 hours or 57 hours and the differenced discharges lagged behind the differenced air temperatures by around 30 hours.

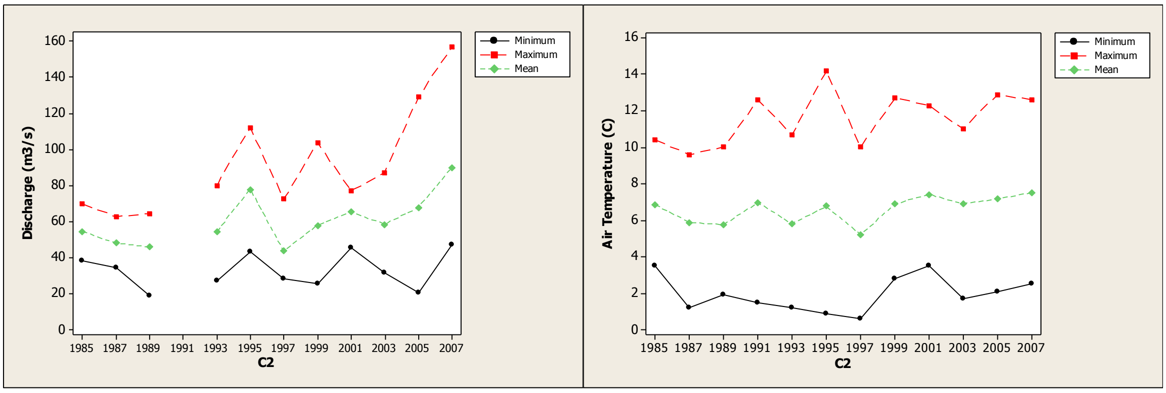


Figure 3.15 Minimum, maximum and mean values for the month of July for each odd year 1985-2007.There is a gap in the data as no discharge data was recorded at station 437 in 1991.

	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Temperature (°C)	-	-1	-0.1	-1.8	1.8	1	-1.6	1.7	0.5	-0.5	0.3	0.3
Discharge (m^3/s)	-	-6.6	-2	-	-	23.5	-34.3	14.3	7.6	-8	8.2	22.3

Table 3.13 Changes in monthly mean air temperature and discharge compared to the previous year sampled.

	No differencing		Seasonally differenced	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.393	33	0.219	36
1987	0.391	33	0.276	27
1989	0.232	33	0.342	33
1991	-	-	-	-
1993	0.429	57	0.213	57
1995	0.540	33	0.330	33
1997	0.243	57	0.204	72
1999	0.363	57	0.181	27
2001	0.330	54	0.306	27
2003	0.527	54	0.355	33
2005	0.642	54	0.279	75
2007	0.459	42	0.347	39

Table 3.14 Lag cross-correlation analysis of July's air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

3.4.4 August

The maximum temperatures in August are lower than those in July implying that overall the summer season is beginning to come to an end. This could be led by the transition from 24 hour daylight in July to slightly fewer sun hours in August which will enhance the diurnal variation within the air temperature record. The discharge record is dominated by the high discharges recorded in 2001, 2003 and 2005. Whilst these are significant events, it is clear that they are not part of a steep melting trend as the average for the year in August does not increase significantly along with the maximum and in 2007 the maximum returns to a value similar to the years prior to 2001.

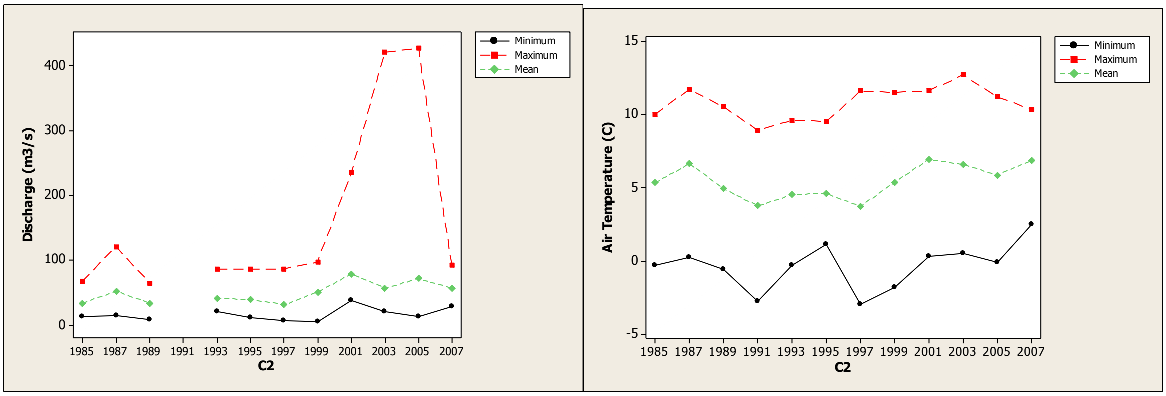


Figure 3.16 Minimum, maximum and mean values for the month of August for each odd year 1985-2007.There is a gap in the data as no discharge data was recorded at station 437 in 1991.

	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Temperature (°C)	-	0.9	-1.7	-1.2	0.8	0.1	-1.9	1.7	1.5	-0.1	-0.8	1
Discharge (m^3/s)	-	18.8	-18.9	-	-	-1.4	-8.3	19.1	28.5	-22.3	15.1	-15.3

Table 3.15 Changes in monthly mean air temperature and discharge compared to the previous year sampled.

	No differencing		Seasonally differenced	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.302	57	0.210	48
1987	0.691	9	0.280	48
1989	0.593	33	0.244	33
1991	-	-		
1993	0.332	54	0.260	57
1995	0.452	33	0.415	33
1997	0.439	33	0.186	54
1999	0.809	33	0.318	24
2001	0.137	57	0.227	48
2003	0.450	33	0.179	33
2005	0.359	24	0.146	21
2007	0.597	69	0.187	66

Table 3.16 Lag cross-correlation analysis of August's air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

For discharge, the autocorrelation remains above 0 until after 80 hours but does oscillate to show a slight diurnal trend. The air temperature data oscillates between negative and positive values after first dropping below 0 at a 9hour lag for years 1987, 1997, 1999 and 2001. After 24 hours, all years apart from 2003, 2005 and 2007 are below 0. This suggests that for August in the last three years studied that air temperature had an influence over runoff for longer than the other years. Once the data has been differenced, the discharge data shows different time lapses for the residuals to no longer have an effect on themselves. The shortest lag is at 24hours for 2007 and the longest lag is 99 hours (4 days) for 1997. For all years except 1989, 2001, 2003 and 2005, once the correlation drops to 0, it becomes and remains negative thus invalidating a relationship between the residuals after the lag time at which 0 is reached. For the other years, the correlations become positive again although nowhere near as close to 1, suggesting that for these years that there is another pattern within the data other than a diurnal signal. In 1999 there is an oscillation on a 48hour timescale. The air temperature autocorrelations that have been differenced correlate positively with each other until a lag of between 18-24hours. After this there are varying patterns which implies that during some years, there is a longer trend within the air temperature data as well as within the discharge data.

3.4.5 September

Due to the data recorder failing during the whole 1991 melt season, interesting question arise when analysing the discharge statistics in figure 3.17. It appears as if the three values are decreasing in 1989 but by 1993 they are significantly higher. Would 1991 have been higher or similar in values to 1989? The cause of the increased runoff in 1993 could have been caused by the increase in minimum temperature and subsequent increase in the mean. If September 1993 was warmer than all other years it would have prolonged the melt season accounting for the relatively high melt for that year. In 2003 there was another extreme discharge event and it is clear that it was only short lived as it has little effect on the mean runoff value.

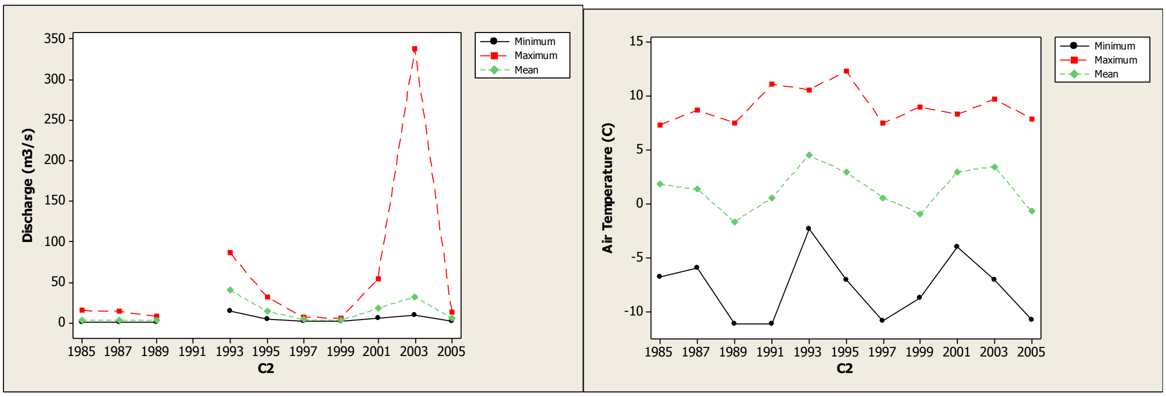


Figure 3.17 Minimum, maximum and mean values for the month of September for each odd year 1985-2005.There is a gap in the data as no discharge data was recorded at station 437 in 1991 and there is no data for 2007 as nothing was recorded for September 2007.

	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Temperature (°C)	-	0.4	-3	1.2	3.9	-1.6	-2.3	-1.7	3.9	0.4	-4.1	-
Discharge (m^3/s)	-	0.3	0.4	-	-	-26.1	-10.4	-0.7	14.7	14.4	-27	-

Table 3.17 Changes in monthly mean air temperature and discharge compared to the previous year sampled.

The cross correlation plots (figure 3.18) have been included in the main text for September as they are very different in appearance to all of the others. The cross correlation for the raw data for most years shows wholly positive correlations even at negative lags and no clear peaks. For the few peaks that are there and are reliable, the lag has reduced to between 0 and 6 hours. This implies that the drainage system has evolved completely and is most effective at moving meltwater through it. However it must be noted that the discharge that is sampled during this month is much less than what was recorded for previous months. The differenced data shows no clear trend with peak lags ranging from -6 to 60 hours.

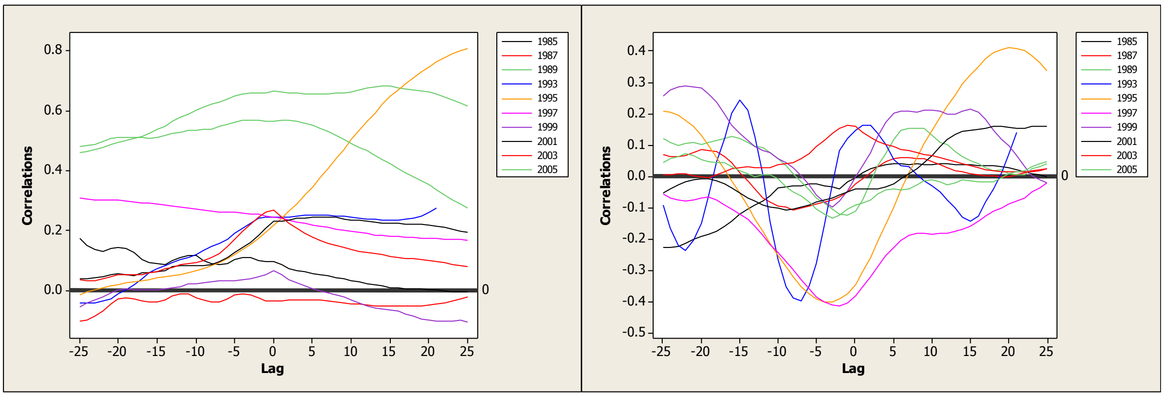


Figure 3.18 Cross correlation function of air temperature and discharge during September. The left plot represents raw data and the right represents differenced data.

	No differencing		Seasonally differenced	
	Maximum Correlation	**Lag hours**	**Maximum Correlation**	**Lag hours**
1985	0.118	-33	0.041	15
1987	-0.012	-33	0.061	18
1989	0.665	0	0.154	24
1991	-	-	-	-
1993	0.253	18	0.163	3
1995	0.807	75	0.411	60
1997	0.310	-75	-0.413	-6
1999	0.065	0	0.212	30
2001	0.236	6	0.160	57
2003	0.268	0	0.163	-3
2005	0.567	6	-0.122	-6

Table 3.18 Lag cross-correlation analysis of September's air temperature and discharge for 1985 to 2007 (odd years only) at 3 hourly observation periods.

In summary, lags of the order recorded here suggest an inefficient drainage system existed during the early stages of the melt season. Lags become progressively shorter as the season continues with air temperature and discharge becoming increasingly in phase but still lag by around 24-48 hours The decrease in lag almost certainly reflects the recession of the snowline and the increase in runoff and although the lags are significantly longer than have been recorded in previous studies. It can be accounted for by the lower slope angle on the GrIS than on valley glaciers in Svalbard or temperate regions and lower temperatures than at lower latitudes.

The negative lag times calculated indicate that peak discharge leads air temperature thereby invalidating a casual relationship. Early season discharge is more strongly correlated with temperature than later in the season (with a few exceptions) suggesting that discharge regimes are dominated by another factor towards the end of the ablation season. Shea et al. (2005) believe that this shift could be dominated by radiation. The lag times calculated for all months are surprising when figure 3.6 is considered. Figure 3.6 shows clear diurnal variation within both variables and the peaks in discharge only lag behind the air temperature by 12 hours. A further study could break the time series down into weekly or daily sections and analyse the lags at this resolution. With a possibility of 1836 days to study, this was beyond the scope of this dissertation.

Descriptive Statistics

Figure 3.19 May

Discharge (m^3/s)	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Minimum	0.1	0.7	0.1	-	2.0	0.7	0.7	0.1	0.5	0.3	0.0	0.5
Maximum	25.9	4.1	2.4	-	14.2	7.6	4.3	1.2	1.5	2.1	10.4	9.1
Mean	6.9	1.7	0.3	-	4.7	2.6	1.4	0.4	0.8	0.6	1.6	2.0
Standard Deviation	8.9	0.7	0.4	-	3.1	1.7	0.7	0.3	0.2	0.3	2.7	1.9
Air Temperature (°C)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	-12.0	-19.5	-15.1	-18.4	-21.8	-6.1	-10.2	-19.9	-11.3	-11.4	-18.8	-9.2
Maximum	10.6	8.8	8.9	8.6	10.1	9.5	8.0	7.7	7.8	9.8	11.3	7.3
Mean	2.2	-0.7	-2.8	-3.1	-2.4	1.8	0.6	-6.0	-1.2	0.5	0.1	-0.7
Standard Deviation	3.9	4.8	4.7	5.1	8.6	3.3	3.2	5.3	4.2	4.0	5.0	3.0

Figure 3.20 June

Discharge (m^3/s)	1985	1987	1989	1991	1993	1995	1997	1999	2001	2003	2005	2007
Minimum	10.0	4.2	2.5		9.1	9.0	1.8	0.4	0.9	2.1	10.3	0.6
Maximum	54.7	99.4	43.6		69.4	69.4	83.5	25.0	69.2	99.8	69.4	112.0
Mean	31.5	39.5	22.8		34.6	42.1	40.3	3.6	21.6	45.9	39.5	41.0
Standard Deviation	12.2	27.5	10.9		19.2	9.0	28.1	4.7	20.4	26.3	20.6	31.4
Air Temperature (°C)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	0.3	-2.6	-1.6	-0.4	-1.6	0.6	0.4	-3.3	-1.7	1.5	0.9	0.1
Maximum	10.7	11.5	10.7	12.2	9.2	10.3	10.6	8.9	10.5	11.1	10.5	11.5
Mean	5.6	5.2	3.2	5.1	4.3	5.5	6.2	2.6	5.2	7.0	6.2	6.3
Standard Deviation	2.2	2.7	2.4	2.2	2.1	2.2	1.9	2.4	2.9	2.0	2.0	2.3

Figure 3.21 July

Discharge (m³/s)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	38.1	34.4	18.8		27.0	43.1	28.3	25.8	45.3	31.7	20.3	47.4
Maximum	69.7	62.8	64.5		79.9	112.0	72.6	104.0	76.9	87.2	129.0	157.0
Mean	54.6	48.0	46.0		54.4	77.9	43.6	57.9	65.5	58.5	67.8	90.1
Standard Deviation	9.2	6.9	11.9		16.7	19.1	11.0	16.9	7.5	12.7	34.2	25.6
Air Temperature (°C)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	3.5	1.2	1.9	1.5	1.2	0.9	0.6	2.8	3.5	1.7	2.1	2.5
Maximum	10.4	9.6	10.0	12.6	10.7	14.2	10.0	12.7	12.3	11.0	12.9	12.6
Mean	6.9	5.9	5.8	7.0	5.8	6.8	5.2	6.9	7.4	6.9	7.2	7.5
Standard Deviation	1.3	1.7	1.8	1.9	1.8	1.9	1.8	1.5	1.5	1.6	2.3	1.9

Figure 3.22 August

Discharge (m³/s)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	13.1	14.5	7.3		20.1	11.3	5.8	5.3	38.4	19.8	13.0	27.8
Maximum	66.9	121.0	64.8		85.8	85.8	86.2	96.8	235.0	421.0	427.0	91.5
Mean	33.4	52.2	33.3		40.8	39.4	31.1	50.2	78.7	56.4	71.5	56.2
Standard Deviation	16.4	29.4	20.0		17.9	23.6	20.9	27.6	37.0	59.6	72.6	18.3
Air Temperature (°C)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	-0.3	0.2	-0.6	-2.8	-0.3	1.1	-3.0	-1.8	0.3	0.5	-0.1	2.5
Maximum	10.0	11.7	10.5	8.9	9.6	9.5	11.6	11.5	11.6	12.7	11.2	10.3
Mean	5.3	6.6	4.9	3.7	4.5	4.6	3.7	5.4	6.9	6.6	5.8	6.8
Standard Deviation	1.8	2.2	2.1	2.4	2.0	2.0	2.4	2.7	2.2	2.5	2.4	1.7

Figure 3.23 September

Discharge (m^3/s)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	0.8	1.0	0.8		13.7	3.9	1.8	1.8	5.8	9.1	1.5	
Maximum	15.0	14.2	7.8		86.6	31.2	6.9	5.1	54.4	338.0	12.8	
Mean	2.9	3.2	3.6		40.1	14.0	3.6	2.9	17.6	32.0	5.0	
Standard Deviation	3.1	2.8	2.3		23.5	7.0	1.6	0.6	12.4	47.8	3.5	
Air Temperature (°C)	**1985**	**1987**	**1989**	**1991**	**1993**	**1995**	**1997**	**1999**	**2001**	**2003**	**2005**	**2007**
Minimum	-6.8	-5.9	-11.1	-11.1	-2.3	-7.0	-10.8	-8.7	-4.0	-7.0	-10.7	
Maximum	7.3	8.7	7.5	11.1	10.6	12.3	7.5	9.0	8.3	9.7	7.9	
Mean	1.8	1.4	-1.6	0.6	4.5	2.9	0.6	-0.9	3.0	3.4	-0.7	
Standard Deviation	2.6	2.5	4.2	4.1	3.0	3.9	4.1	3.7	2.3	3.2	4.2	

3.5 Net Radiation

Net radiation is recorded at GC-Net stations all over Greenland that came into operation in 1999. The data from JAR-2 are available to compare to the air temperature and discharge records although there is no radiation data until 2 June 1999. The AWS record data at hourly intervals so every third value had to be extracted from the net radiation record. This was a lengthy and time consuming session writing Macros.

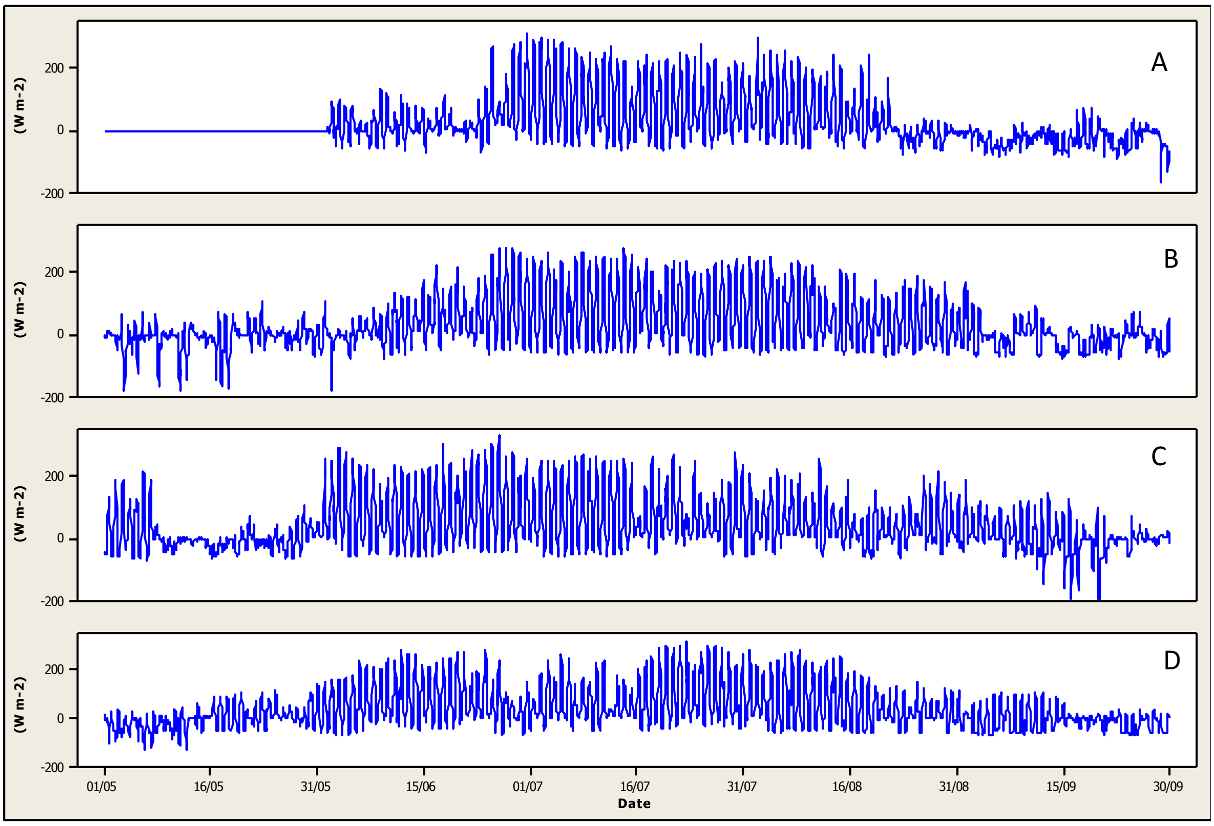


Figure 3.19 Net radiation time series for (A) 1999, (B) 2001, (C) 2003, (D) 2005.

The net radiation time series show diurnal cycles which would be expected given the varying heights of the sun throughout the day. Following the trend rather than the diurnal oscillations, in 1999, (A), despite the missing data in May, the magnitude of this cycling is much less in June, and from mid-August onwards than it its for July and early August, when there is much higher net radiation during the middle of the day. After the peak in net radiation on 24 June (from 13.91 W m^2 to 290.59 W m^2), there is a slow and steady decrease in net radiation (with the exception of one hour on 4 August at 252.00 W m^2) until 23 August when the net radiation drops sharply (from 241.54 W m² to 17.28 W m²). In 2001, (B) net radiation starts to increase on 15 June and peaks on 25 June (255.20 W m²), before slowly decreasing and dropping sharply on 1 September (from 168.00 W m² to 29.88 W m²). 2003, (C), shows a different pattern with large net radiation values and diurnal variation between 1 and 8 May. Between 8 and 31 May, there is less variation and low net radiation than any other year for this period. However, on 31 May this rises sharply and remains high until 15 September although it is a period punctuated with a number of low net radiation readings. After 15 September there is a high proportion of negative values recorded. 2005, (D), would have shown the most even trend in the data rising steadily to a peak on 31 July before slowly falling again by the end of August if July wasn't punctuated by 5 days of very low net radiation. This could be accounted for by days of cloud cover. These descriptions are summarised in figure 3.20 depicting the summary statistics for each year.

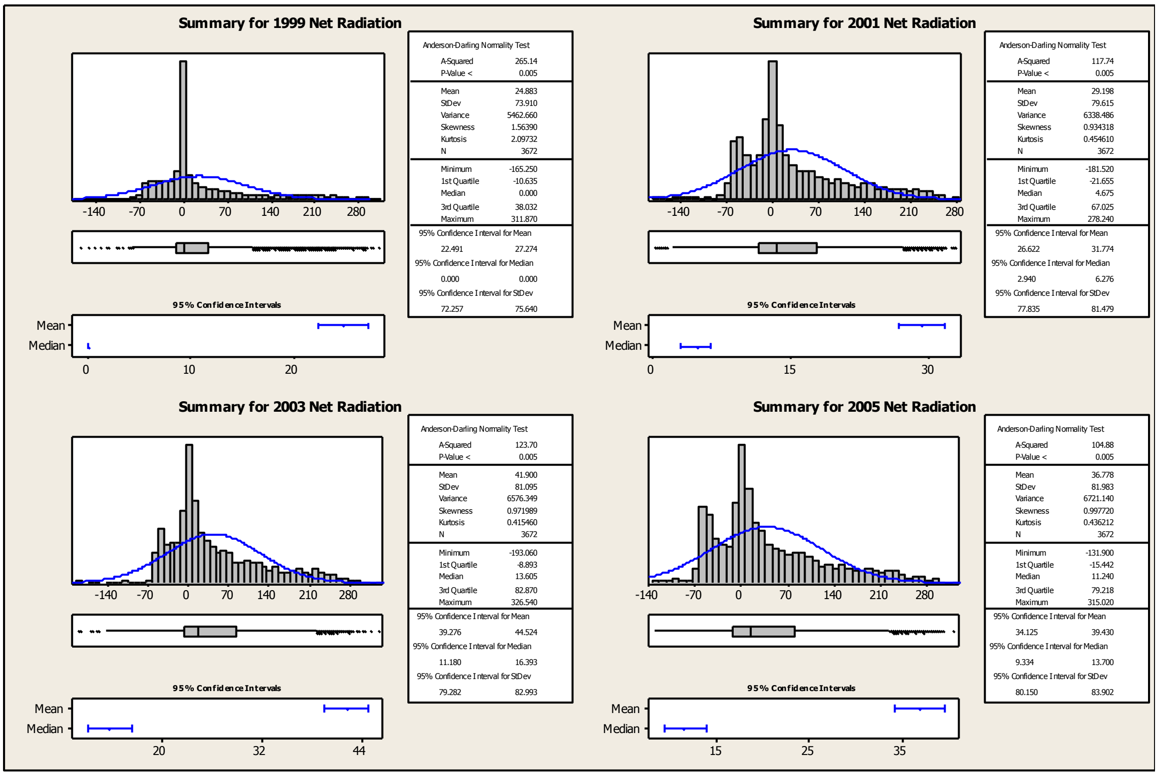


Figure 3.20 Graphical representation of the summary statistics for net radiation data, years 1999-2005

Comparison with Air Temperature and Discharge Data

Whilst in the previous sections of this chapter, it has been argued that air temperature and discharge are related. This section puts forward the idea that both net radiation and air temperature have an impact upon meltwater runoff. Here each season is presented alongside air temperature and discharge data. Further analyses have not been carried out due to the temporal resolution of the data sets and few available years to study. Autocorrelation diagrams have also been calculated and are on p64 In figure 3.29.

1999

There is a clear transition within the discharge record from negligible runoff values to almost 100m³/s in a very short space of time. This coincides with the onset of large diurnal fluctuations in the net radiation data and the increased maximum daily net radiation. The air temperature record also shows signs of increasing but not to the same extent as the net radiation or discharge data sets. At the end of the season when net radiation falls, within a couple of days, the amount of runoff being recorded at station 437 has fallen to almost 0m³/s. Surprisingly, the Pearson correlation values show air temperature to be better correlated with discharge than net radiation and air temperature itself shows a lesser correlation with net radiation, the variable that is commonly assumed to control it. The cross correlation plots calculated between the variables are also much lower in correlation than for discharge and air temperature as described in section 3.3. The peak lags were also all negative thereby invalidating this statistical test as a way of analysing the relationship between the variables.

	Discharge	Air Temperature
Air Temperature	0.706	
Net Radiation	0.428	0.579

Table 3.24 Pearson correlation between the three variables.

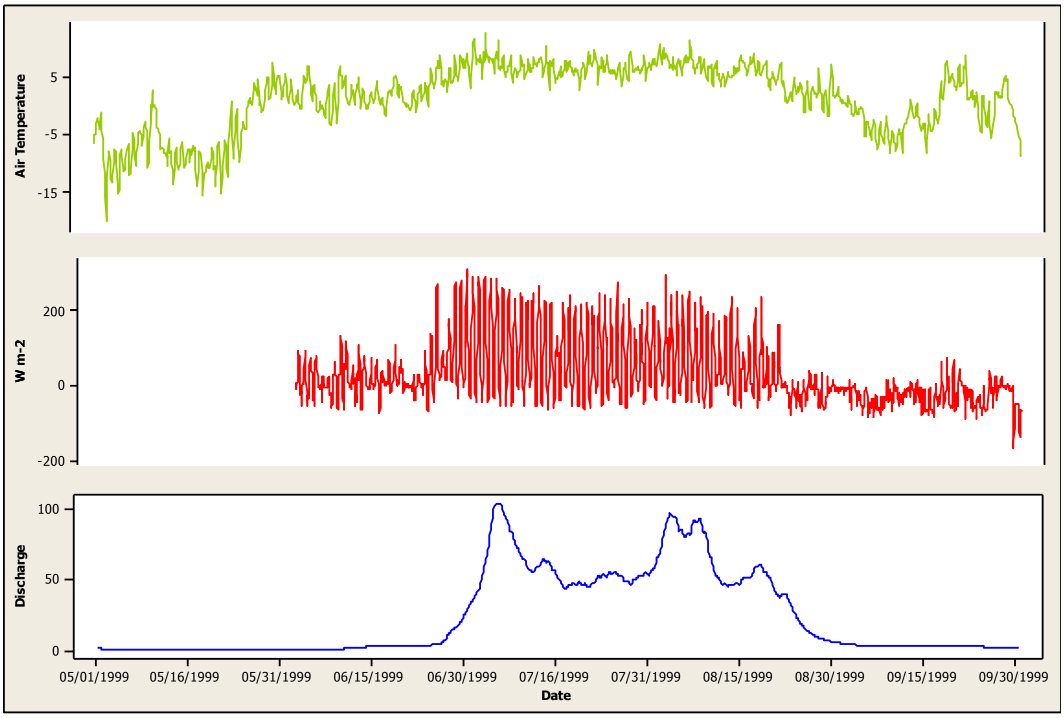


Figure 3.21 Time series showing air temperature, net radiation and discharge data for 1999.

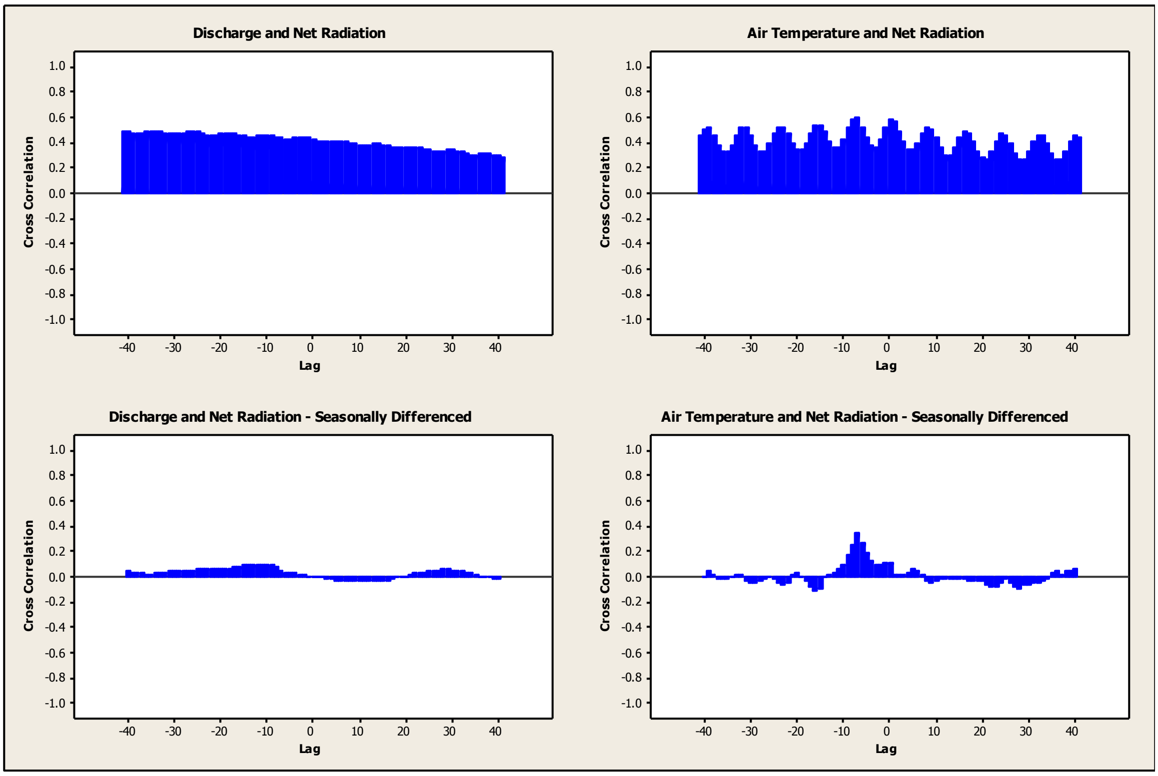


Figure 3.22 Cross correlation plots of the three variables using raw and seasonally differenced data to remove the diurnal cycling.

2001

The net radiation data had an inconsistent episode on 18 May and the AWS recorded 999 W m-2. This was not verified although verification was requested from GC-Net so the event was assumed to be a malfunction of the AWS. The three variables are not well correlated in 2001 although again, the initial rise in seasonal melt coincided exactly with a rise in daily maximum radiation. The large short-lived discharge event in mid-August does not coincide with events of equal magnitude in the air temperature or net radiation records. This implies that there was another variable exerting control over the rate of melt water or that there was a single flood event possibly caused by almost instantaneous opening of a conduit, breaching of a dam or glacial earthquake. The event is short lived and discharge levels actually decrease to below the preceding conditions before rising again.

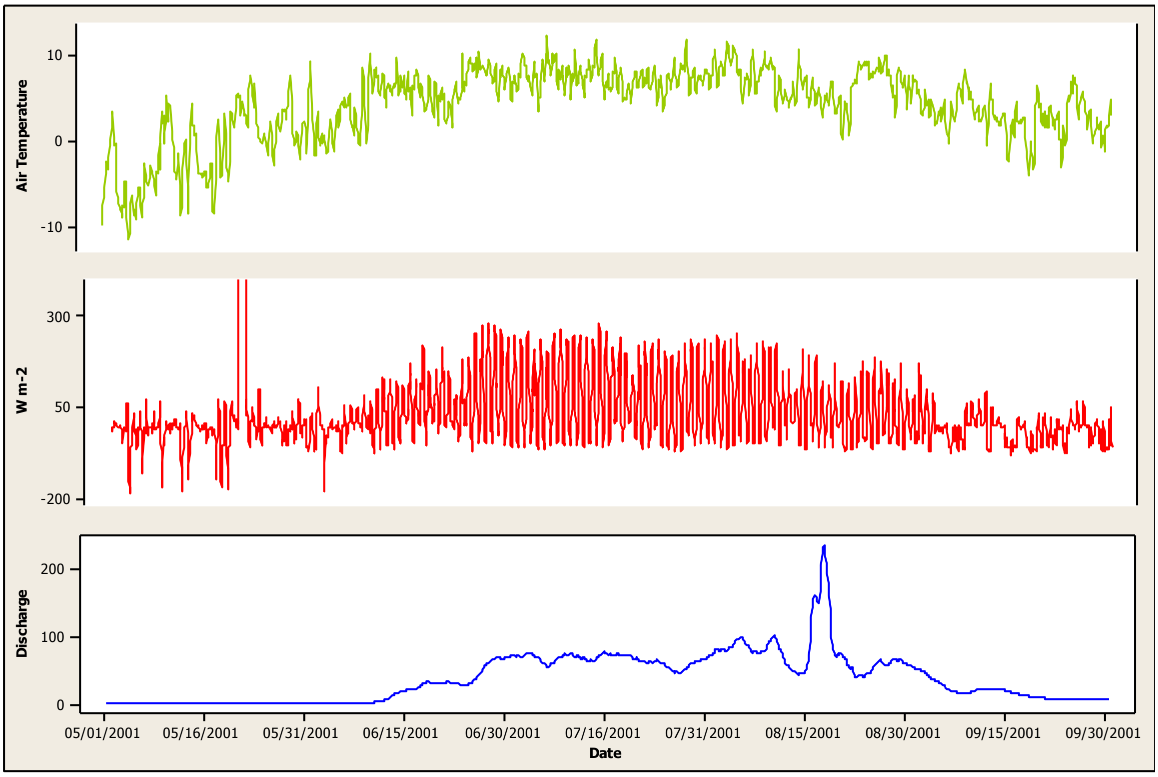


Figure 3.23 Time series showing air temperature, net radiation and discharge data for 2001.

	Discharge	Air Temperature
Air Temperature	0.568	---
Net Radiation	0.183	0.350

Table 3.25 Pearson correlation between the three variables.

In 2001, the highest correlation found between the variables is between air temperature and discharge and the correlation between discharge and net radiation is considerably less than it was in 1999. It is possible that the disparity between the two years' correlations is due to the flood event in mid-August. The cross correlation is also much less in 2001 and despite detrending the air temperature and net radiation data, a seasonal cycle still exists at a 24 hour oscillation.

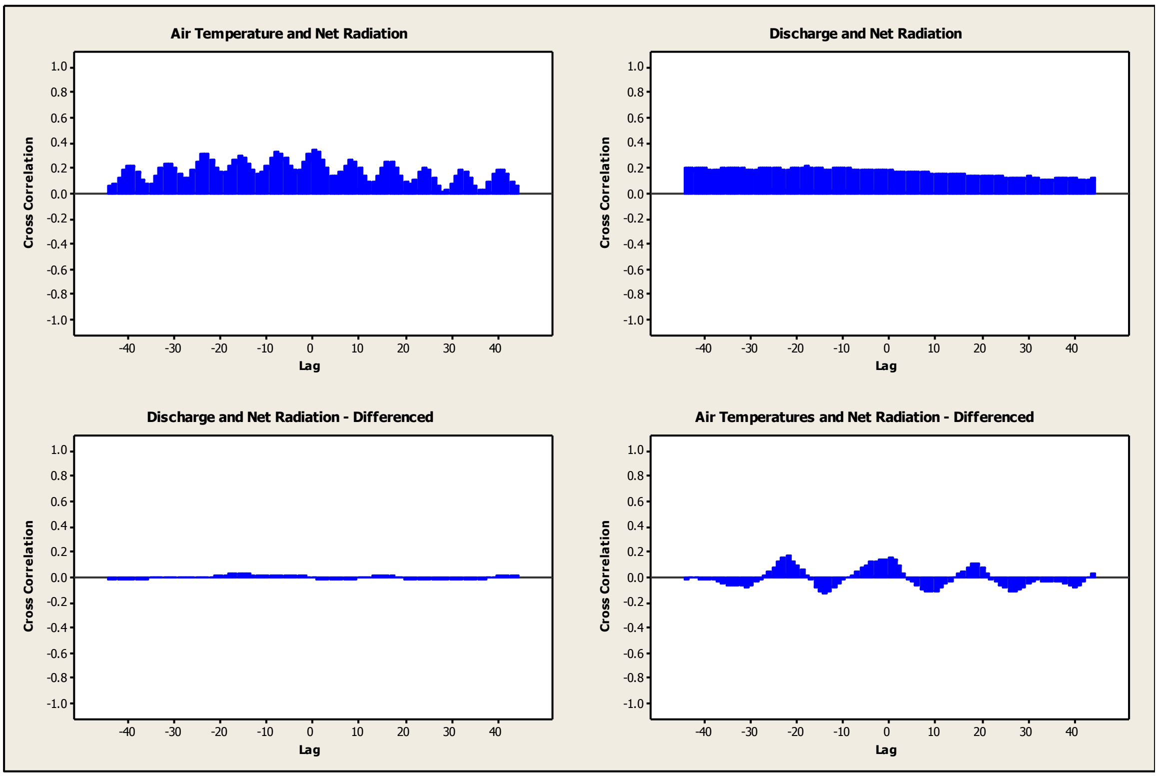


Figure 3.24 Cross correlation plots of the three variables using raw and seasonally differenced data to remove the diurnal cycling.

2003

During the 2003, summer melt season air temperature and net radiation are relatively well correlated with a value of 0.503 (figure 3.26).

	Discharge	Air Temperature
Air Temperature	0.429	
Net Radiation	0.216	0.503

Figure 3.26 Pearson correlation for all three variables

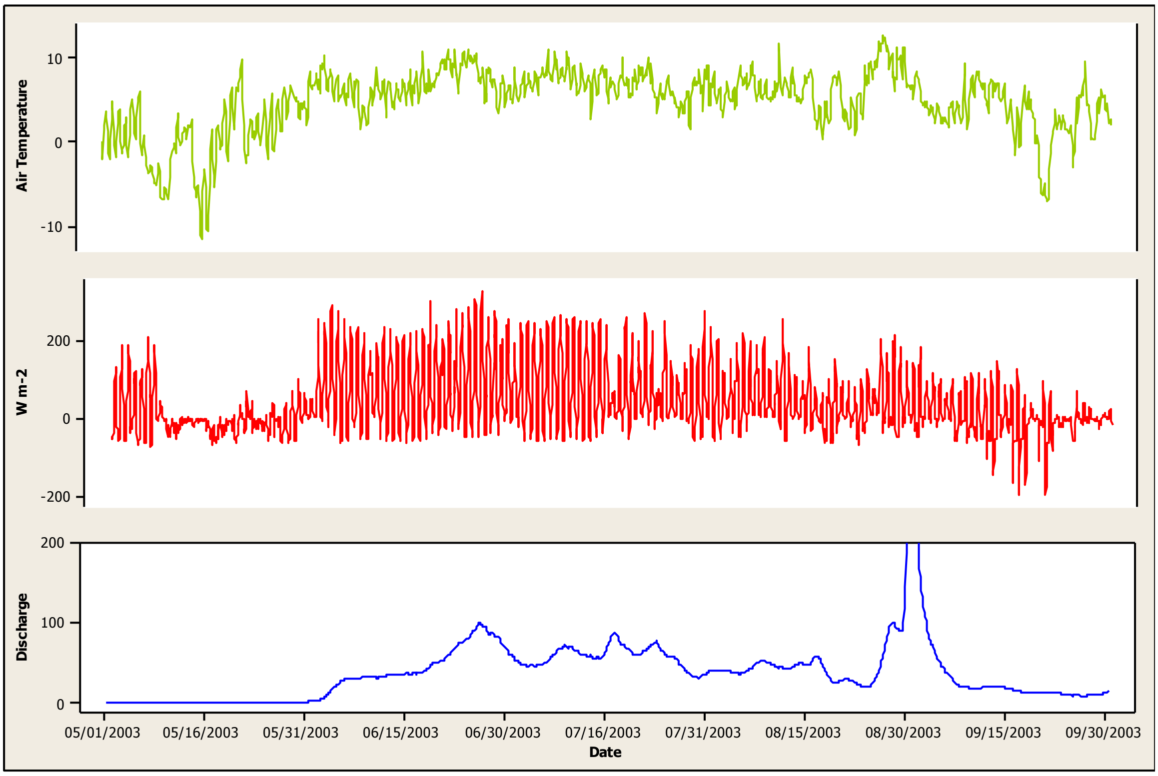


Figure 3.25 Time series showing air temperature, net radiation and discharge data for 2003.

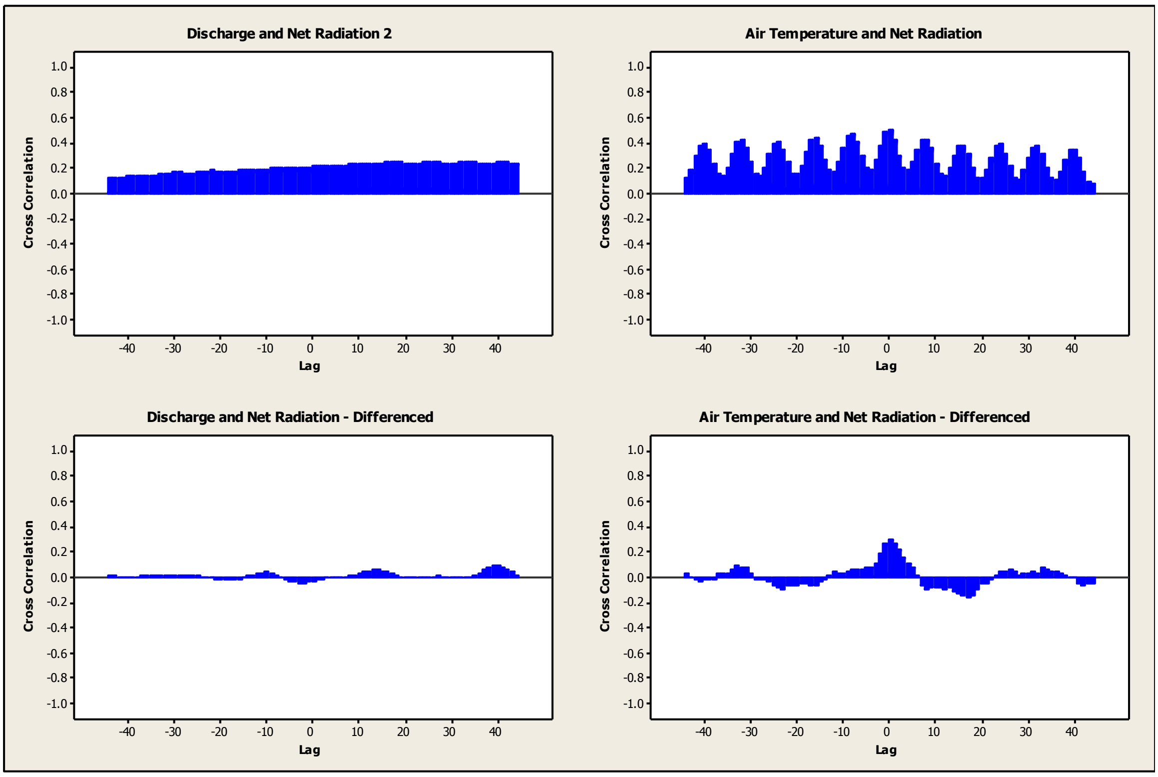


Figure 3.26 Cross correlation plots of the three variables using raw and seasonally differenced data to remove the diurnal cycling.

The time series (figure 3.25), again provides evidence that suggests that the onset of melting at Paakitsoq coincides with a large rise in net radiation when it rises on 3 June. The peaks and troughs of the melt water record loosely follow the net radiation series but air temperature is a closer match. Again, the short-lived discharge event does not appear to be caused by changes in net radiation or air temperature although there is a peak in air temperatures 2 days before the discharge peak. This may be circumstantial evidence however as the discharge begins to rise before the air temperature and it is reliably assumed that discharge will not influence air temperatures to the same degree as recorded here.

2005

There is another anomaly within the radiation data for 2005 and values of 999W m-2 were recorded again, it is assumed to be a malfunction of the AWS. The highest correlation between the variables in 2005 was 0.515 for air temperature and discharge, the relationship between discharge and radiation was low, at 0.239 but not the lowest recorded (table 3.27). A very similar relationship exists between the variables to 2003; the discharge loosely follows the net radiation trend but neither variable can account for the flood event on 30 July. The cross correlations are similar in shape to all other years although the correlations recorded for differenced discharge and net radiation residuals are markedly lower than any other year.

	Discharge	Air Temperature
Air Temperature	0.515	
Net Radiation	0.239	0.374

Table 3.27 Pearson correlation for all variables

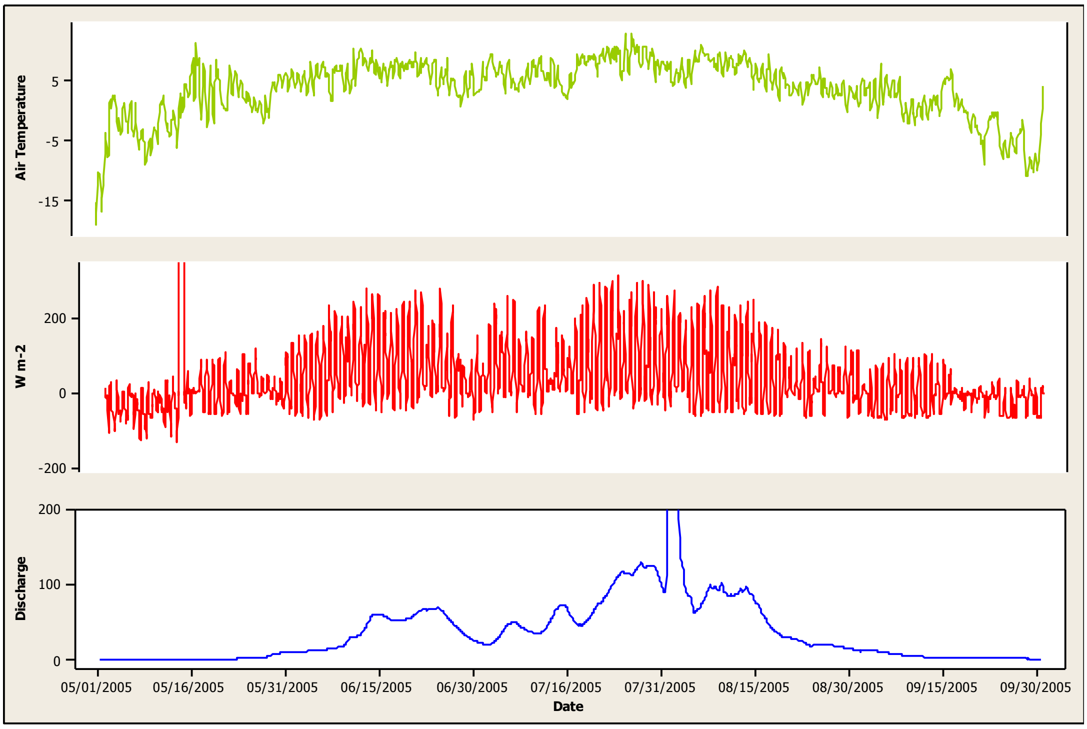


Figure 3.27 Time series showing air temperature, net radiation and discharge data for 2005.

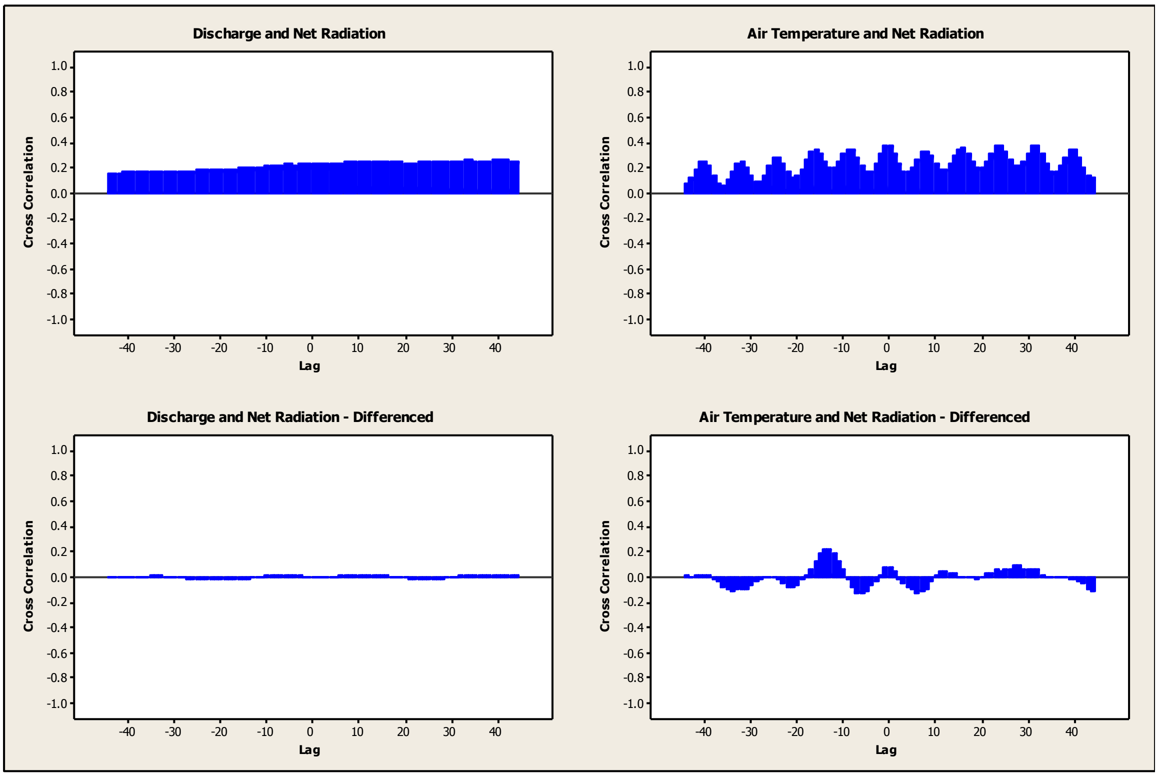


Figure 3.28 Cross correlation plots of the three variables using raw and seasonally differenced data to remove the diurnal cycling.

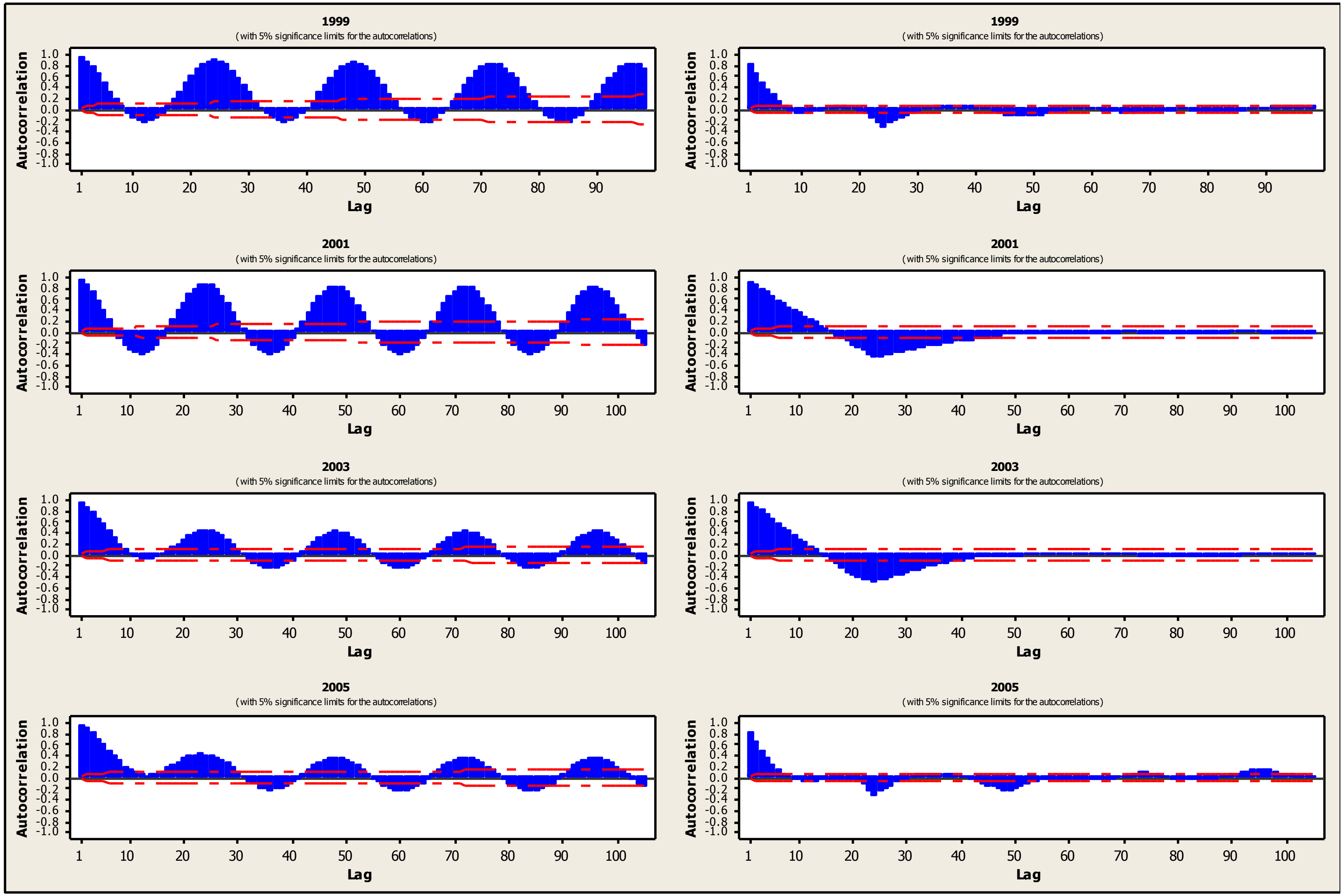


Figure 3.29 AutoCorrelation graphs for net radiation. The left ones show raw data and clear seasonal cycling whilst the right ones were computed using detrended data and the seasonal component has been removed.

Section 3.5 has shown that the onset of melting in the Paakitsoq basin happens at the same time as a transition in the net radiation pattern. For 1999 and 2001, the end of the melt season coincided with a drop in net radiation. However, for the last two years, discharge has fallen to below $5m^3/s$ before the major shift in the amount of net radiation. For autocorrelation the repetitive peaks in correlation all occur at the same lag times so it can be assumed that all years oscillate on the same time scale for net radiation. The differences come from the peaks after the initial trough at 24 hours as over the years studied they become progressively less well correlated ~ 0.8 in 1999 to only ~ 0.4 in 2005.

Multiple regression model statistics were calculated and these show that with the exception of June 1999 that seasonal regression statistics decrease as the season progresses and with the exception of August 2001, the r^2 values follow the same pattern. Inter annually, r^2 values and multiple regression coefficients are decreasing for May, 0.656 to 0.337 but increasing for September 0.247 to 0.609. The three months in between show no pattern and fluctuate between rising a falling (table 3.28). The r^2 values indicate how well net radiation and air temperature explain the variation within the discharge data. The highest r^2 value calculated was 0.591 in August 2001 but many of the other months presented significantly lower r^2 values although there is still positive correlation meaning that net radiation and air temperature can account for up to 59% of the variance although most values are below 0.25 indicating that the relationship is weak and that there are other variables impacting on the proglacial discharge.

	May	June	July	August	September
1999	0.652	0.196	0.325	0.294	0.247
	0.425	**0.038**	**0.189**	**0.198**	**0.056**
2001	0.657	0.426	0.236	0.243	0.268
	0.320	**0.182**	**0.055**	**0.591**	**0.071**
2003	0.427	0.390	0.201	0.106	0.287
	0.182	**0.152**	**0.04**	**0.011**	**0.082**
2005	0.377	0.308	0.493	0.361	0.609
	0.142	**0.095**	**0.243**	**0.130**	**0.371**

Table 3.28. Multiple regression statistics by month for net radiation, air temperature and glacial discharge for the years 1999 – 2005. Lower value in bold is r^2.

4. Discussion

Relationships between the hydrological and meteorological time-series, are used to characterise the response of the glacierized part of the catchment to meteorological forcing throughout the ablation seasons measured, (1985-2007). The hydrological response of a glacial drainage basin is broadly dictated by climate and topography with glacier ablation being the main source of meltwater in glacial basins. The annual runoff regime depends largely on the annual distribution of radiation, air temperature, humidity, cloud cover and precipitation (Figure 4.1) and therefore no glacial runoff regime will be the same. Hodson et al., (2001) suggest however, that air temperature is the primary controlling factor over glacial ablation with the impact of other variables being less important when considering seasonal trends. High annual changes in ablation and runoff that occur as a result of meteorological conditions are typical phenomena in glaciated catchments of the Arctic and are seen in the Paakitsoq basin where seasonal discharge ranges from $0.79 m^3/s$ and $97.57 m^3/s$. Meteorological forcing is the primary control on glacial melt, but the quantity and rate of response of discharge to this forcing is modified by the extent of the snowpack and by the changing flow paths through which the melt water drains the system (Hodson et al., 1998) (figure 3.1).

Studies that take a systematic approach to investigate glacial hydrological responses must take into account the intensity of the melting process and the evolution of the glacial flow structure (Hock and Hooke, 1993). Typically glacial basins have pronounced annual and seasonal runoff variations and this is especially true during the summer months for mid-latitude glaciers but to a lesser extent for high latitude glaciers. This dissertation has shown little consistent change at the annual, seasonal or monthly time scales although inferences can be made about changes in snowpack recession and hydrological system evolution as the variables' relationship to themselves and each other changes over the melt season.

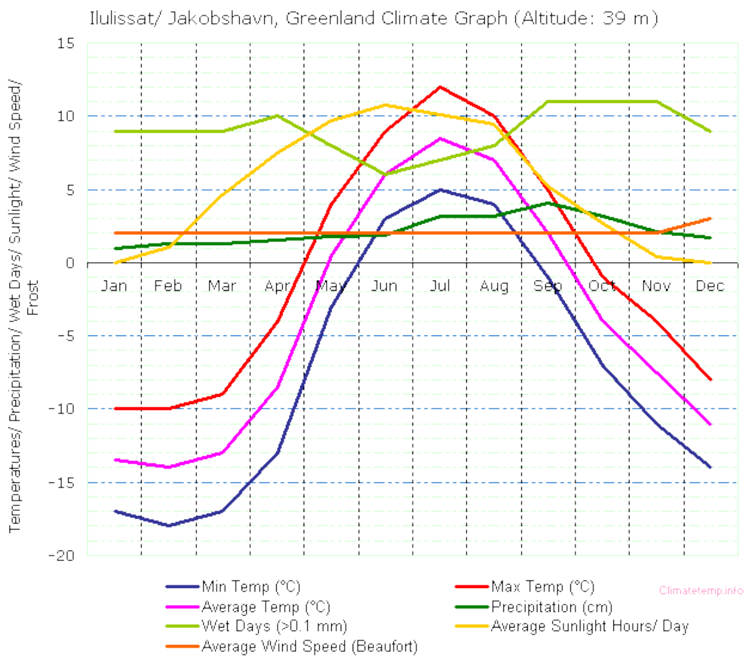


Figure 4.1 Average climate variables for Ilulissat/Jakobshavn (45km from the Paakitsoq basin). (Source: ClimateTemp, 2010)

Monthly Change

Over the course of the season, the shape of the hydrograph changes (figure 3.6). Willis and Bonvin, (1995) found this to also be the case for the Haut Glacier d'Arolla, Switzerland, during the 1993 melt season. The differences arise in the timing and magnitude of the changes. In Switzerland - a temperate glacier – the discharge ranges from $0m^3/s$ to $5.5m^3/s$ whereas, at Paakitsoq, the seasonal average discharge values range from $0.79m^3/s$ to $97.57m^3/s$. This difference in magnitude is assumed to be caused by the difference in glaciated area between the temperate glacier ~$6km^2$ and the Paakitsoq basin in Greenland, $286km^2$. Figure 4.2 a and b show the difference between the temperate glacial basin, Haut Glacier d'Arolla and the Paakitsoq basin. Whilst May and June appear to be similar in extent of diurnal cycling, July at Paakitsoq precedes that of Haut Glacier d'Arolla as there is significant clear diurnal oscillation whereas the equivalent oscillation does not come into effect in Switzerland until August but it lasts all the way through to September. September in the Paakitsoq basin shows extremely subdued diurnal signals if any.

The decrease in lag time seen between the months (figure 3.6) is the consequence of an evolving glacial drainage system which perhaps switches from a slow distributed drainage network to a fast channelized system (Willis et al., 2002). From the LandSat images (figure 1.4),(The LandSat images were taken in 2001 but it is presumed that a similar pattern occurs every year, perhaps at slightly different times), it can be seen that the snowline has retreated significantly between July and August. Less supraglacial lakes are present suggesting that the melt water is being transferred from the surface to the ice margin through an englacial, supraglacial or a subglacial drainage system; this would explain the decrease in lag times between July and August (on average 46hours to 39 hours). A decrease in time lag is interpreted as either, the establishment of a surface-bed connection as crevasses in the lower part of the glacier are now open and efficiently transporting snowpack runoff to the glacier bed (Shepherd et al., 2009, Zwally et al., 2002), or the switch from a distributed glacial network to a channelized one initiated by removal of the snowpack.

a b

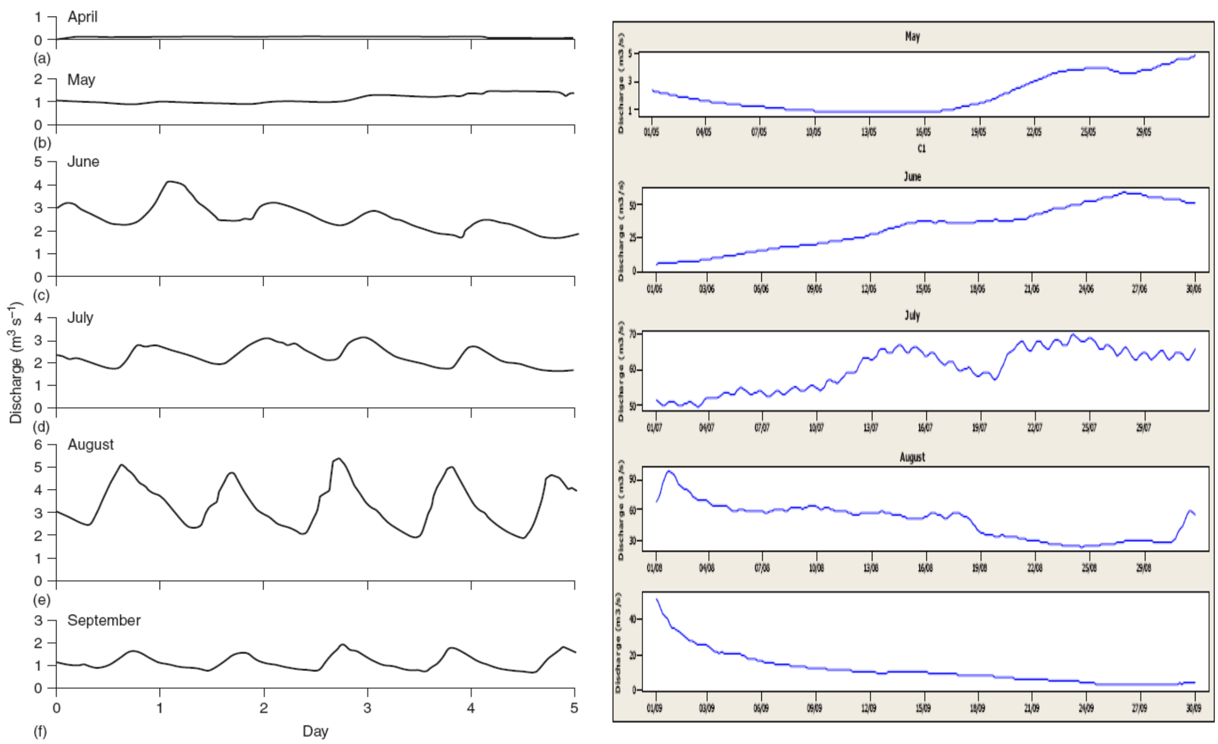


Figure 4.2 A and 4. 2B. (A) Changing shape of proglacial hydrographs from Haut Glacier d'Arolla, Switzerland, 1993 (Source: Willis and Bonvin, 1995) (B) Changing shape of the average monthly hydrographs for the Paakitsoq Basin between 1985 and 2007.

Fountain, (1996) suggested that an observed seasonal increase in diurnal stream flow variation is the product of faster flow routing at the glacier surface rather than an enlargement and increased efficiency of the subglacial hydraulic system (Willis et al., 2002). The diurnal discharge variation is seen within all sampled years (figure 3.12) and lasts a number of days before the hydrograph returns to its previous state of no diurnal variation. This is not what one would expect to see when considering the previous work of Hodgkins, (2001) and Gurnell et al., (1994) on valley glaciers but is perhaps a functioning of the Arctic drainage system. If the cause of the new diurnal pattern was indeed the evolution of the hydrological system, hydrological pathways would most likely remain open until the temperatures dropped significantly enough to close them again meaning that discharge would remain elevated for longer.

Previous day’s discharge and temperature have typically been proven to present the strongest seasonal correlations for discharge and this can be seen in the diurnal pattern within the discharge record and the autocorrelation of discharge although the calculated lag times from cross correlations do not represent this relationship.

Annual Melt Season Anomalies

1987 Tedesco, (2007) found that the 1987 melt season reduced to be less than 100 days, this coincides with a reduction in the minimum and mean temperatures for the year yet surprisingly at Paakitsoq, the mean and maximum values are elevated. 1987 also displayed the second highest correlation between air temperature and discharge.

1991 Air temperatures drop on 7 May and remain low for 6 days. Unfortunately due to a lack of discharge data, it is not possible to analyse the impact of this unseasonal temperature drop upon the melting.

1995 There are much larger shifts in runoff for this year than any other year. In September the there are sporadic air temperatures and little sign of the trend displayed in the other years. However, of interest, on 12 September there is a marked peak in air temperatures and two days later on 14 September, discharge responds and rises. This implies that for an individual unseasonal event in September, air temperature directly impacts upon runoff at a lag of 48 hours.

1997 In May, when air temperatures seem to have most impact upon meltwater production, a significant low temperature recorded on 31 May has no effect on the discharge time series. In august, a peak air temperature on 13th August, could have caused the collapse of an ice dam or triggered a small glacial earthquake because 24 hours later, there is a typical type 1 discharge fluctuation within the runoff time series (figure 1.4).

1999 had a very late start to the summer melt season with no discharge recorded until 30 June. This could be attributed to the air temperatures in May staying consistently low and below 0°C. Air temperature was also lower than all other years during June and normally in May and June temperatures fluctuate between negative and positive values daily. The autocorrelation calculations also showed a 48 hour oscillation within the discharge data which had not been seen before.

2003 demonstrated the highest cross correlation in May at 0.42. Hanna et al (2008) observed an important increase in Greenland temperatures and snowmelt for this year and this coincided with the extreme discharge event that happened late in the season. The cause of the event may be the breaching of an ice dam or the opening of new conduits brought about by an increased amount of melt water production.

2005 The same could be said about this melt season as temperatures and snowmelt remained high in 2005. Additionally, there were high sea surface temperature anomalies in the North Atlantic warming the air masses moving onto the land.

2007 There are sizeable dips in temperatures at the end of May lasting for over 10 days where temperatures remain below 0°C. Other than this, Tedesco (2007) found that an overall rise in melt area corresponds with the highest mean discharge of the study period and melting lasted ~25-30 days longer for this season over the whole GrIS. At Paakitsoq, the melt season began late at the end of June but unlike other years, runoff hadn't reduced to almost 0m^3/s by the end of September, it was in fact rising again. The values recorded for July had most impact on adjusting the seasonal averages for all variables.

Net Radiation

The energy supply to and the subsequent utilization of this energy in high latitude and low altitude glacial environments is very different to that of low latitude, high altitude glacial basins. The high latitudes have even greater annual variations in net radiation and air temperature, with long periods of the year when air temperatures are below freezing point and the net radiation is nil. A major difference between high latitude and mid to low latitude basins is that incoming radiation is received continuously during the summer months. Consequently diurnal variations in incoming radiation and subsequent air temperatures are not as marked as at lower latitudes over the summer melt season and diurnal variability in the glacial runoff is therefore relatively subdued (Gurnell et al., 1994)(figure 4.2b)

As net radiation and therefore sensible and latent heat increase over the summer melt season (Willis, 2005), runoff generally increases as the snowpack is depleted. Once ice is exposed, the albedo drops dramatically and when coupled with increases in net radiation the spring and summer melt rises. Early season melt is temperature dependent when the transient snow line remains low and the hydraulic properties of the snowpack limit both diurnal discharge variability and a rapid hydrological response. As the melt season progresses, melting snow and ripening of the snowpack, induce a glacier-wide decrease in albedo (Shea et al., 2005) and a more structured net radiation-discharge response is observed. The multiple regression equation was applied to the net radiation, air temperature and discharge data and the statistics show with the exception of June 1999 that seasonal regression statistics decrease as the season progresses. And with the exception of August 2001, the r^2 values follow the same pattern. Inter annually, r^2 values and multiple regression coefficients are decreasing for May but increasing for September. The three months in between show no pattern and fluctuate between rising a falling (table 3.28).

Section 3.5 demonstrated that the onset of melting in the Paakitsoq basin for the years 1999, 2001, 2003 and 2005 occurs in sync with a transition in the net radiation pattern. For 1999 and 2001, the end of the melt season also coincided with a drop in net radiation. However, for the last two years, 2003 and 2005 discharge has fallen to below $5 m^3/s$ before the shift in the amount of net radiation. There were only net radiation data available for 4 years used in this study. Once more data has been collected and analysed, the long term trend in the relationship between the variables will become clearer as currently two seasons display one trend and another two years display another leaving the relationship between net radiation and discharge unclear. Unfortunately due to software constraints, the data was not able to be processed using wavelet software which would have shown the periodicity within the relationship and enhanced the seasonal trends that occur within the three variables.

Seasonal Evolution of the Drainage System

The seasonal evolution of the diurnal hydrograph and the changes in the relationship between meteorology and discharge all indicate a difference in the functioning of the meltwater system in the middle of the season to the beginning and end (table 3.7 and figure 3.12). Either side of the dates in table 3.7 the proglacial discharge was high and variable and intra-seasonal, seasonal, and monthly hydrographs showed little diurnal cycling although this was present in the air temperature record throughout the year. In the middle of the season, the discharge record was much more invariable but with a clearer diurnal cycle and the correlations between discharge, air temperature and net radiation were much stronger. Overall there is a steady response of runoff to meteorology in the early melt season but an unexpected response at the end. The temporal transition from a hugely variable discharge signal with little or no diurnal cycling to a more invariable signal with clear diurnal cycling is brief compared with the length of the melt season May to September (Figure 3.12). The response of discharge to meteorological inputs is substantially different at Paakitsoq to that identified by Gurnell et al., (1992, 1994),and (Tangborn and Rasmussen, 1976) where the response was progressive and steady over the course of the melt season and there were no short term transitions or events as have been identified in figure3.2.

The principal control on these contrasting periods appears to be the seasonal variation in melt water storage although this does not account for the disappearance of diurnal cycling in the discharge record towards the end of the melt season. This temporal variation in the magnitude and variability of discharge and its response to meteorological inputs can also be understood in terms of a seasonal meltwater storage pattern. In the early part of the melt season supraglacially stored meltwater dominates the hydrograph. The meltwater therefore contributes to proglacial discharge but does not respond to energy fluxes at the hourly or diurnal time scale because it was produced in the early weeks of the melt period and subsequently released discontinuously at varying long term delays (days rather than hours). Once the supraglacial lakes have drained or reduced in size (figure 1.4) their contribution to proglacial discharge becomes less and any new melt water produced daily begins to dominate the hydrograph and the diurnal cycle becomes visible. The discharge does not vary on a daily basis as much as air temperatures due to the influence of stored water being released and the flow of water melted at the glacier base contributing continuously to the hydrograph. The saturation of the snowpack causes it to breakdown and water is able to flow freely across the glacier surface to the drainage channels. With little storage occurring at the surface because the snowline has retreated to its seasonal minimum, surface melting contributed to the diurnal hydrograph at shorter lags and the system appears more responsive to diurnal forcing. As a result, the relationships between meteorology and discharge are stronger and diurnal cycles are clearer in the middle of the season.

However, often, cold high latitude glaciers do not have very developed englacial drainage systems and they lack subglacial drainage systems altogether meaning that the drainage system cannot evolve as the summer progresses as it does on temperate glaciers. It is known through the work of Alison Banwell that the Paakitsoq basin does have a subglacial drainage system so the drainage system must evolve throughout the summer but retains some of the characteristics of a high latitude glacier in terms of the very long calculated lag times between discharge and meteorological forcing. Considering figure 3.6, the following model of meltwater storage is hypothesised. Melting is effectively absent at Paakitsoq until May 16th. From then until ~19 June, there is storage in the snowpack. Extensive saturation of the snowpack occurs because the glacier is relatively flat with a cold impermeable surface; this causes water to accumulate at the surface in greater volumes than at temperate glaciers and supraglacial lakes form that can be seen in the LandSat images (figure 1.4a). Release of this water after 19 June is rapid and it runs directly over the snow surface to the ice margin in supraglacial and englacial drainage channels and potentially penetrates the glacier and propagates fractures to its base before joining subglacial drainage channels. This is significantly different to the steady drainage recorded at Storglaciaren (Ostling and Hooke, 1986) and South Cascade Glacier (Tangborn and Rasmussen, 1976) but it accounts for the non-progressive seasonal regime.

Late season discharge decreases significantly despite higher temperatures as englacial or subglacial conduits are contracting. This could mean that meltwater is stored within the glacier over winter and is then released earlier than the assumed beginning of the melt season (May) when temperatures start to rise again, this is seen in the time series of the whole year with a rise and subsequent fall in discharge in April before the main melt season begins (figure 4.3). It is uncertain however whether this can definitely be attributed to the release of water stored over winter and further research and field studies would be needed to could confirm this.

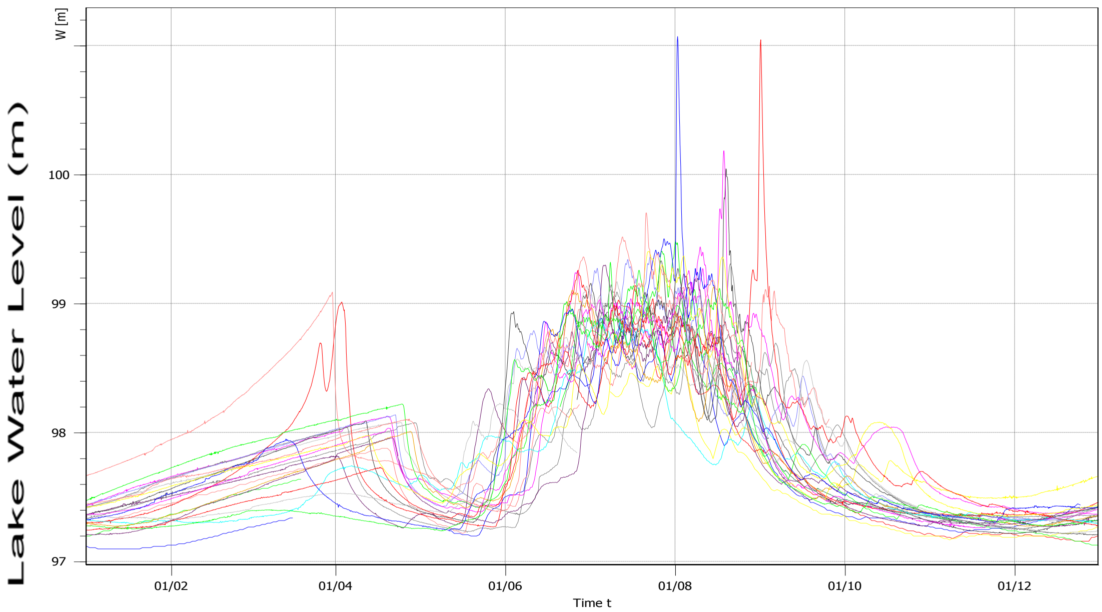


Figure 4.3 Times series of lake levels for Lake 187 for the whole year. Notice the recorded variable is lake level (m) but this translates directly into discharge thought the use of a discharge rating curve. (Source: Asiaq, 2008)

Seasonal Snow Distribution

The shape of the hydrograph is often very much controlled by the depth and extent of snow cover in the basin (Hodgkins, 2001). Snow and firn act as aquifers on a glacier serving to dampen discharge peaks and reduce the amplitude of diurnal flow variability. Meteorological forcing is the primary control on glacial runoff, but the rate of response is modified by the extent of the snowpack across the system and by the changing flow paths though which melt water flows to the ice margin. The permeability of snow has a large influence upon the phasing of discharge with respect to meteorological forcing and also on the magnitude of discharge peaks since water may be stored for a long time in the snowpack.

A receding snowline supports the rapid hydrological response of ice surfaces which do not store substantial amounts of meltwater, thus leading to a more pronounced diurnal variability (Shea et al., 2005). The analysis indicates that the recession of the snowpack across the glacial portions of the basin has an important effect on the catchment area contributing to runoff and the lag between energy inputs and meltwater discharge outputs. During May and June, rising air temperatures exert little direct or diurnal control over the discharge patterns but in July there are clear diurnal cycles. The work of Nienow et al., (1998) showed that the recession of the snowline coincided with the emergence of diurnal cycles within the discharge time series at Haut Glacier d'Arolla. If this is also true of the Greenland ice sheet then inferences can be made as to when the snowpack is depleted at Paakitsoq from the date of diurnal oscillation onset (figure 3.12 and table 3.7). There seems to be no annual trend in the onset with dates ranging from 12 June to 20 July and there are no similar studies on the GrIS to compare the results to.

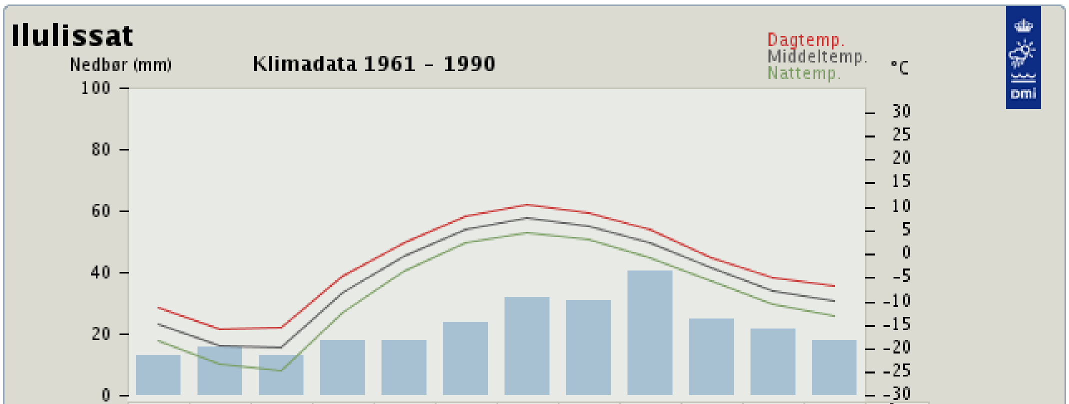
The works of Nienow et al., (1998), Sharp and Boon, (2003) and Willis et al., (2002) have confirmed the delaying impact of a snowpack on glacial discharge for valley glaciers and it is assumed to be similar on the GrIS. The lags are always significantly larger for the Paakitsoq basin 0-108 hours than for Austre Broggerbreen (Hodson et al., 1998) and the alpine Haut d'Arolla glacier (Gurnell et al., 1992). This infers that more water is being stored supraglacially, englacially or subglacially at the Paakitsoq glacier or that slower transport of meltwater through the glacial system to proglacial runoff occurs because of differences in glacier slope, slower rates of snow pack recession and ponding of meltwater on the surface. On John Evans Glacier, Ellesmere Island, Canada, the delay in runoff caused by the snowpack is around 2 weeks on the lower glacier and over 3 weeks on the upper glacier even though the snow depths are lower than those recorded at temperate glaciers (Boon and Sharp, 2003). The lags calculated at Paakitsoq (up to 108 hours) are not as long as those at John Evans Glacier, but they are significantly higher than the lag times recorded at temperate glaciers. Since high latitude glaciers are colder than temperate ones, the ice is largely impermeable allowing for the development of supraglacial lakes which will enhance the delay between melting and proglacial discharge. These lakes can last in Greenland for between 2 and 10 weeks and empty quickly over 1 or 2 days as supraglacial streams unblock and water drains to the ice margin or fractures propagate to the ice bed allowing water to flow subglacially. In Svalbard, these lakes commonly drain in late May and early June but at Paakitsoq the lakes are still clearly visible in the 2001 LandSat images (figure 1.4) in July and August. The drainage of supraglacial lakes in Paakitsoq may occur much later in the season than elsewhere, due to the long lasting snow cover throughout the summer months, accounting for the short-lived discharge events in 2001, 2003 and 2005. Due to the late onset of positive temperatures, and high net radiation snowpack recession is also late and it will take more time for temperatures to encourage the enlarging of glacial fractures. This would delay the propagation of these fractures to the bed and in turn delay the onset of movement of melt water from the glacier surface to subglacial water pathways, hence why large glacial outbursts occur later in the summer season than in mid-latitude regions. The LandSat images in figure 1.4 show clear evidence of ponding and storage of water on the glacial surface. Once the snowpack has receded by August 1st, fewer supraglacial lakes are present implying that the melt water produced previously has been discharged and that current meltwater is being transported relatively efficiently through the glacial meltwater system to monitoring station 437. Unfortunately due to a lack of further LandSat images, this cannot be proven.

Impacts of precipitation

Links between atmospheric circulation, regional climate and glacial discharge have been explored by (Lawler et al., 2003) using correlation and multiple regression analyses at a monthly time scale. They found that discharge is more sensitive to regional temperatures than to precipitation. This is because seasonal variations in the discharge and temperature records are largely synchronous whilst the high discharge season and times of maximum precipitation are out of phase. Furthermore in Greenland, much of the precipitation will fall as snow and is therefore not available immediately for runoff whilst it melts. Seasonal changes in surface conditions and water routing can affect the glacial response to a rainfall event. The presence of snow and an inefficient drainage system in early summer can dampen the effects of precipitation on glacial discharge as water is stored within the snowpack. Later in the melt season, the removal of the snowpack and the emergence of glacier ice leads to a more efficient hydrological network and means that rainstorms can be detected in proglacial discharge signals.

The presence of snow causes a delayed response to rainfall or snowmelt because water available at the surface takes time to pass through the snowpack before entering the glacial drainage system. If rainfall occurs over snow, it soaks into the snowpack like a sponge and the rainwater then behaves as snowmelt. Depending on the cold content and liquid water deficiency of the snowpack, it is also possible that precipitation does not contribute to runoff at all. Under these conditions, the water generated from rainfall or surface melting is used to ripen the snowpack. When the cold content and water deficiency are satisfied the water moves through the snowpack and appears as delayed runoff. This is a common scenario when the maximum snow cover is present in the basin. As the melt season progresses, both the depth and extent of snow cover decrease and melting occurs at a higher rate because of temperature changes throughout the summer months. Therefore, a relatively faster response of the basin to precipitation occurs in the summer (Singh & Singh, 2001). As figure 4.4 shows, on average most precipitation to Ilulissat (45km from Paakitsoq) falls during the month of September although July and August also receive over 30mm of precipitation. Especially in September and to some degree in late-July and August, the impact of precipitation on the hydrograph will be more pronounced (although the angle of slope will slow the movement of it towards Lake

187) assuming that it falls as rain. If it falls as snow, energy is needed to melt it before it can runoff and contribute to the hydrograph. The analysis has shown decreasing lag times between air temperature and discharge implying that seasonal evolution of the drainage system is taking place each year making it more efficient at transporting precipitation or meltwater to the ice margins.



	JAN	FEB	MAR	APR	MAJ	JUN	JUL	AUG	SEP	OKT	NOV	DEC	ÅR
Nedbør (mm)	13	16	13	18	18	24	32	31	41	25	22	18	266
Nedbørdage	4	4	4	5	4	5	5	5	7	5	6	5	60
Dagtemp.	-11.3	-15.9	-15.7	-4.7	2.3	8.0	10.3	8.6	5.1	-0.7	-4.9	-6.7	-1.9
Middeltemp.	-14.8	-19.6	-19.9	-8.2	-0.5	5.1	7.5	5.9	2.4	-3.1	-7.8	-9.9	-5.0
Nattemp.	-18.3	-23.5	-24.7	-12.6	-3.6	2.2	4.5	3.0	-0.7	-5.9	-10.8	-13.1	-8.3
Solskinstimer													

Figure 4.4 Average climate data from Ilulissat, Greenland. Translations: **Nedbor**: Precipitation, **Nedbordage:** Days with rain, **Dagtemp:** day temperature, **Middeltemp:** daytime average temperature **Nattemp:** night temperature (Source: Danish Meteorological Institute, 2010)

The melt seasons in 1985 and 2003, were characterised by relatively high pressure over the Norwegian Sea and relatively low pressure over Greenland, This circulation regime bought abnormally large and frequent storms to Southern Greenland and less frequently to Western Greenland (Box et al., 2009). This meant that Western Greenland and the Paakitsoq region received less precipitation than the average during these years. Little or no snow accumulation in the ablation zone would produce a larger than average melt season given the reduced amount of snow available for melting before glacial ice ablation. 2003 especially was noted in section 3 due to the extreme runoff event that occurred in early September (30 August – 5 September). Due to the fewer number of storms and precipitation events earlier in the season, the glacial drainage system could have been evolving for a much longer time period than normal. If this was the case then the drainage system may have evolved to such an extent that a precipitation event would have a significant effect on the hydrograph. Another theory is that a lack of winter or early season precipitation would have enhanced the melting of the glacier ice. Due to its impermeability, supraglacial lakes formed and the rapid discharge of one or more of these lakes could account for the short lived high discharge event in early September. Table 3.18 shows that the lag between temperatures and discharge was 0 hours for September 2003, which would imply that due to the lack of accumulation that season there was no snow available for melting and therefore air temperatures were directly impacting upon the ice on very short timescales. Unfortunately due to a lack of rainfall data, there is no way to test this hypothesis. And contrary to this suggestion, discharge would not be expected to rise by the amounts seen in September 2003 from a single precipitation event. Also considering the low average monthly precipitation amounts in Figure 4.6, it seems unlikely that rainfall events will be seen in the Paakitsoq hydrograph due to the large surface area of the basin and low slope. If precipitation data were available then the data would need to be analysed on the diurnal timescale to be able to detect any changes

Global Climate Patterns

Global climate change is brought about by regional changes to atmospheric circulation patterns which can be described by positive and negative pressure anomalies (Lawler et al., 2003). Regional scale climate controls glacier mass balance through its effects on local precipitation, cloud cover and air temperature. Therefore teleconnections exist between atmospheric circulation and glacial mass balance and runoff (Willis, 2005). As with glacier mass balance, regional climate controls annual runoff largely through its effects upon precipitation and air temperature. However the effect of climate variability on annual discharge depends on the sensitivity of the system to these variables. With little precipitation recorded at Ilulissat, the Paakitsoq hydrological system does not appear to be sensitive to precipitation. Interannual runoff variability also depends on the percentage of the catchment that is covered in ice. For the Paakitsoq basin this is over 87%.

(Hanna et al., 2008) observed significant increases in Greenland margin summer temperatures and measured temperature and snowmelt records in 2003 and 2005 which corresponds to the extreme discharge events measured at

Paakitsoq in those years. They also recorded a highly significant correlation of Greenland and Northern Hemisphere temperatures since the early 1990s and collectively this suggests that an expected response of the GrIS to global warming may well be emerging. This signal can be set against a background of natural variability including regional changes in atmospheric circulation related to the NAO (Figure 4.5).

The North Atlantic oscillation (NAO) is characterised by two distinct phases, positive and negative and the maximum impact is felt during the boreal winter. When the NAO is positive atmospheric temperature over the Azores is significantly high and is low over Iceland. This results in strong air flow over the North Atlantic and Western and Northern Europe bringing warm and wet conditions. The western Greenland area however experiences cool and dry conditions. A negative phase of the NAO is associated with high pressure over Iceland and low pressure over the Azores. In this case meridional flows of cold Arctic air predominate and North West Europe experiences cold dry conditions and western Greenland is warm and wet.

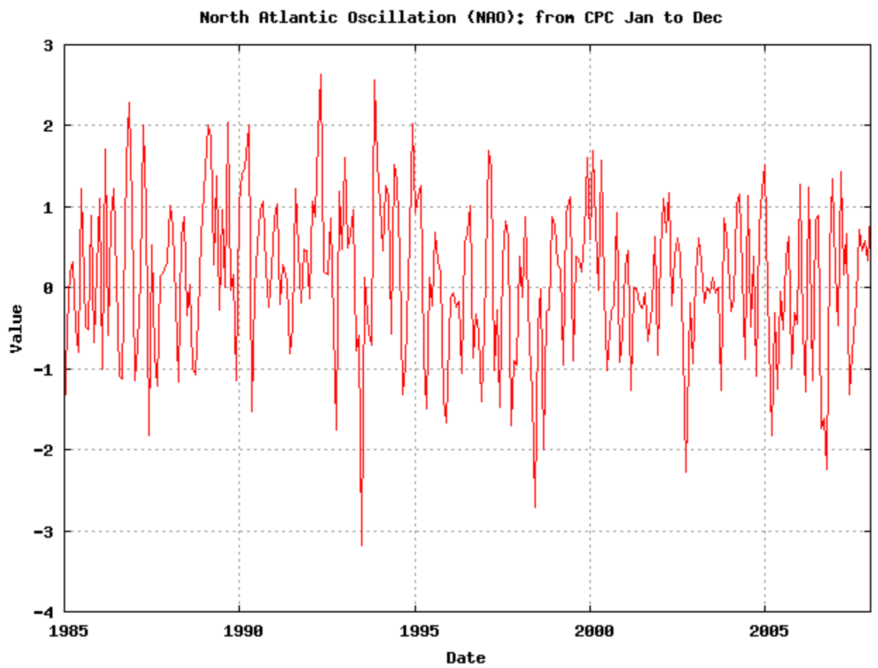


Figure 4.5 North Atlantic Oscillation values by month, 1985 -2005 (Source: Climate Info, 2010)

Lawler et al., (2003) found that generally discharge displays an inverse correlation with NAO reflecting the inverse association of temperature with NAO. For the same reason discharge-NAO correlations are weakest in the summer. Discharge tends to respond to both high and low frequency variations in regional climate and atmospheric circulation. The discharge cycles seen in the Paakitsoq region are most closely related to air temperature records which in turn are linked to the more general annual patterns of atmospheric circulation over Greenland. So whilst the NAO may be influencing temperatures, it is inversely impacting upon runoff.

Looking again at the yearly discharge cycles in figure 4.3 and the by Lawler and Wright, (2003) both studies have reported declines in spring discharge especially in March and April. Lawler and Wright, (2003) linked this decrease directly to spring cooling and it was later linked to a strengthening of the April NAOI and a modest weakening in South Westerly circulation over Iceland and West Greenland. The cause of the increase in proglacial discharge in April and subsequent decrease are not yet known in Paakitsoq but the NAO could be the cause of the decline in late April.

Glacial Earthquakes

Glacial earthquakes are becoming more frequent as rising temperatures cause increased movement within the GrIS. Glacial earthquakes are caused when glaciers lurch unexpectedly and can produce tremors as strong as 5.1 on the moment-magnitude scale (which is similar to the Richter scale). Glacial earthquakes are most common in July and August and have more than doubled in number since 2002 (Tsai and Ekstrom, 2007) with over 11 recorded at nearby Jakobshavn Isbrae. This research backs up that of (Zwally et al., 2002) as they suggest that the cause of the earthquakes is meltwater seeping to the base of the glacier and lubricating it, causing it to lurch and funnel all of the glacial runoff towards the sea in single discharge events. The results also suggest that major outlet glaciers can respond to changes in climate conditions much faster than originally assumed. These earthquakes that have been recorded at Jacobshavn Isbrae may have been the cause for the anomalously large discharge events in 2001, 2003 and 2005 although this may just be coincidental timing. Figure 4.6 shows the increase in yearly glacial earthquake numbers and the concentration of them within the months of July. August and September, notice that the non-glacial earthquakes do not show seasonal variation. Another interesting point to note it that there is an increase in glacial earthquakes in April and then a reduction in May coinciding with the discharge records in Figure 4.3.

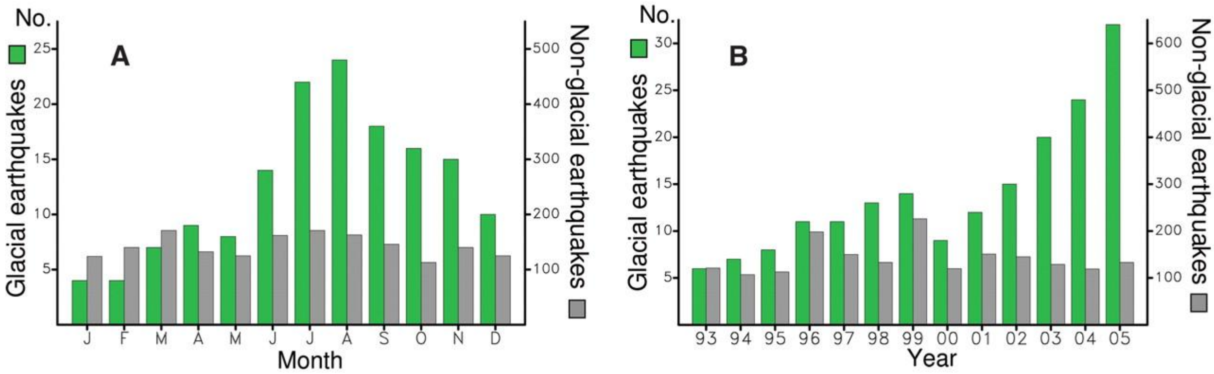


Figure 4.6 (**A**) Histogram showing seasonality of glacial earthquakes in Greenland. Green bars show the number of detected Greenland glacial earthquakes in each month during the period 1993 to 2004. Gray bars show the number of earthquakes of similar magnitude detected elsewhere north of 45°N during the same period. (**B**) Histogram showing the increasing number of Greenland glacial earthquakes (green bars) since at least 2002. No general increase in the detection of earthquakes north of 45°N (gray bars) is observed during this time period. (Source: (Tsai and Ekstrom, 2007)

If the flux of water reaching the bed is large enough then a distributed hydrological system won't be able to effectively transport the water to the glacial margin and parts of the system will either have to expand or water will be stored within the system. A switch between a distributed hydrological system to a channelized one can be brought about by extreme rainfall events, high melt rates or glacial earthquakes (Willis, 2005). For the years 2001, 2003, and 2005, before each extreme discharge event there was however a decrease in discharge immediately before suggesting that water was being retained within the glacier and once this barrier had been removed, water floods to the ice margin. This theory does account for the reduction in discharge before the event but cannot explain why the discharge levels are so high during it implying that excess water must be draining from somewhere in the system – perhaps the drainage of a supra-glacial lake.

4.2 Critiques of Methods

Although trends have been demonstrated within the data, there are some discrepancies regarding data analysis and collection. The automatic nature of sample collection means that there are gaps in the sample record that sometimes have gone unnoticed or unrepaired for over long time periods. These gaps meant that in order to get an even spread of data for this dissertation, that every odd year would be analysed. Due to this partial record, it is not appropriate to make solid conclusions regarding the data. If a full record was available, analysis could be carried out for every melt season and a clearer picture would emerge.

Should more research be carried out on this data it would allow for deeper analysis into the relationships between discharge and meteorology. Time has been a major constraint during this project as to analyse every year or to change the resolution and analyse each week or each day during the summer melt season would require many more hours at this level and even more should the time series be analysed in more depth using more statistical tests and wavelet analysis. Wavelet Analysis was used by Lafreniere and Sharp, (2003) to compare seasonal and annual variability in the hydrological regimes of two rivers in Canada. They concluded that wavelet analysis is a fast and effective tool to quantify the relationships between variables especially when dealing with large datasets. This dissertation had intended to use wavelet analyses on the Paakitsoq data but unfortunately the computer package was not received in time for the analysis to be carried out and the scope of this dissertation had to be changed to only include statistical analysis.

4.3 Further research

More work is required on the Paakitsoq basin to clarify the relationship between meteorological factors and glacial discharge and to explore further what other variables exert control over glacial runoff. Once this relationship has been effectively established at the diurnal scale, other basins on the GrIS should be investigated to confirm the relationships. Wavelet analysis would be an ideal tool to enable this. As previously stated, whilst the relationships have been explored for many temperate glaciers, more work is required on cold based, high latitude glaciers.

5. Conclusions

The statistical analysis performed by Hanna et al, (2008) suggests that the climate of Southern Greenland is responsive to northern hemisphere warming. As a consequence, the GrIS is likely to be vulnerable to ongoing warming, with a predicted increase in Greenland temperatures of ~1℃ - ~8°C by 2100. The effect of climate change on runoff from glacierized basins is hard to quantify (Willis, 2005), since climate change occurs at local, regional and global scales. Annual or melt season runoff may increase or decrease in the short term depending on the magnitude and timing of the climate shifts as this will affect the patterns of precipitation and snow accumulation.

The previous studies on the relationships between glacial discharge and meteorology, the forward modelling approach as used by Arnold et al., (1998); Nienow et al., (1998); Willis et al., (2002); Sharp and Boon, (2003) and the inverse modelling approach that uses statistical analysis to look at the relationships (Lafreneire and Sharp, 2003, Hodgkins, 2001, Hodson et al., 1998, Shea et al., 2005) have mostly focussed on temperate valley glaciers and no work had been done before to quantify the relationship on the Greenland Ice Sheet. This dissertation has applied simple statistical techniques to discrete time periods to provide an initial analysis into how air temperature, net radiation and discharge are related in the Paakitsoq drainage basin.

Whilst few, if any clear relationships have emerged within the data, similarities do exist between the valley glacier relationships and seasonal drainage evolution. Braithewaite (1981) found that even though net radiation is the largest energy source for melting, correlation between net radiation and discharge is often poorly correlated whist air temperatures correlate moderately well with discharge. The same is true for the Paakitsoq basin although the average correlation between air temperature and discharge is only 0.564 ± 0.13, which means that air temperature can account for just over half of the variance in discharge. The meltwater hydrology of the Paakitsoq basin is complicated and rapid discharge fluctuations are superimposed upon a classic diurnal discharge regime that seems to respond to air temperature fluctuations. Due to there being no other studies at this latitude or on a sub-basin of an ice sheet, drainage evolution and relationships can only be inferred. Like the Haut

Glacier d'Arolla, the Paakitsoq data shows clear diurnal variation within the discharge time series. The onset of diurnal cycling also coincided with the rise in daily net radiation although the cessation of this cycling is not in sync for half of the years studied.

There appears to be an increasing trend in both inter-seasonal discharge and air temperature but this is punctuated with seasons that do not follow this increase. Either, more years would need to be studied, or data from elsewhere on the ice sheet could confirm this conclusion. From the inconclusive results, it is not possible to successfully suggest how the supraglacial, englcial or subglacial drainage pathways are evolving inter-annually, intra-annually and monthly. Other sources of data such as aerial photographs, ground penetrating radar data, and more meteorological variables would be required in order to successfully quantify and explain not only the relationship between air temperature and discharge but also to understand the seasonal evolution of the basin's drainage system.

6. Bibliography

ABDALATI, W. & STEFFEN, K. 1997. The apparent effects of the Mt Pinatubo eruption on the Greenland ice sheet melt extent. *Geophysical Research Letters,* 24**,** 1795-1797.

ABDALATI, W. & STEFFEN, K. 2001. Greenland ice sheet melt extent: 1979-1999. *Journal of Geophysical Research-Atmospheres,* 106**,** 33983-33988.

ARNOLD, N., RICHARDS, K., WILLIS, I. & SHARP, M. 1998. Initial results from a distributed, physically based model of glacier hydrology. *Hydrological Processes,* 12**,** 191-219.

BALLANTYNE, C. K. & MCCANN, S. B. 1980. Short-lived damming of a high-arctic ice-marginal stream, Ellesmere-island, nwt Canada. *Journal of Glaciology,* 25**,** 487-491.

BAMBER, J. L., ALLEY, R. B. & JOUGHIN, I. 2007. Rapid response of modern day ice sheets to external forcing. *Earth and Planetary Science Letters,* 257**,** 1-13.

BENN, D.I. AND EVANS, D.J.A. 1998. Glaciers and Glaciation. Edward Arnold, London. 734 pp.

BOON, S. & SHARP, M. 2003. The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier. *Geophysical Research Letters,* 30.

BOX, J. E., YANG, L., BROMWICH, D. H. & BAI, L. S. 2009. Greenland Ice Sheet Surface Air Temperature Variability: 1840-2007. Journal of Climate, 22, 4029-4049.

BRAITHWAITE, R. J. 1981. On glacier energy-balance, ablation, and air-temperature. *Journal of Glaciology,* 27**,** 381-391.

BRAITHWAITE, R. J., OLESEN, O. B. & THOMSEN, H. H. 1992. Calculated variations of annual ice ablation at the margin of the Greenland ice-sheet, West Greenland, 1961-90. *Journal of Glaciology,* 38**,** 266-272.

BRAUN, L. N., WEBER, M. & SCHULZ, M. 2000. Consequences of climate change for runoff from Alpine regions. *Annals of Glaciology, Vol 31, 2000,* 31**,** 19-25.

CHYLEK, P., DUBEY, M. K. & LESINS, G. 2006. Greenland warming of 1920-1930 and 1995-2005. *Geophysical Research Letters,* 33**,** 5 pp.

DAS, S. B., JOUGHIN, I., BEHN, M. D., HOWAT, I. M., KING, M. A., LIZARRALDE, D. & BHATIA, M. P. 2008. Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. *Science,* 320**,** 778-781.

FENN, C. R., GURNELL, A. M. & BEECROFT, I. R. 1985. An evaluation of the use of suspended sediment rating curves for the prediction of suspended sediment concentration in a proglacial stream. *Geografiska Annaler Series a-Physical Geography,* 67**,** 71-82.

FOUNTAIN AG. 1996. Effect of snow and firn hydrology on the physical and chemical characteristics of glacial runoff. Hydrological Processes 10: 509-521.

GORDON, S., SHARP, M., HUBBARD, B., SMART, C., KETTERLING, B. & WILLIS, I. 1998. Seasonal reorganization of subglacial drainage inferred from measurements in boreholes. *Hydrological Processes,* 12**,** 105-133.

GREGORY, J. M., HUYBRECHTS, P. & RAPER, S. C. B. 2004. Climatology - Threatened loss of the Greenland ice-sheet. *Nature,* 428**,** 616-616.

GURNELL, A. M., CLARK, M. J. & HILL, C. T. 1992. Analysis and interpretation of patterns within and between hydroclimatological time-series in an alpine glacier basin. *Earth Surface Processes and Landforms,* 17**,** 821-839.

GURNELL, A. M., HODSON, A., CLARK, M. J., BOGEN, J., HAGEN, J. O. & TRANTER, M. 1994. Water and sediment discharge from glacier basins - an Arctic and alpine comparison. *Variability in Stream Erosion and Sediment Transport***,** 325-334.

HANNA, E., HUYBRECHTS, P., JANSSENS, I., CAPPELEN, J., STEFFEN, K. & STEPHENS, A. 2005. Runoff and mass balance of the Greenland ice sheet: 1958-2003. *Journal of Geophysical Research-Part D-Atmospheres,* 110**,** 16 pp.

HANNA, E., HUYBRECHTS, P., STEFFEN, K., CAPPELEN, J., HUFF, R., SHUMAN, C., IRVINE-FYNN, T., WISE, S. & GRIFFITHS, M. 2008. Increased runoff from melt from the Greenland Ice Sheet: A response to global warming. *Journal of Climate,* 21**,** 331-341.

HOCK, R. 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology,* 282**,** 104-115.

HOCK, R. 2005. Glacier melt: a review of processes and their modelling. *Progress in Physical Geography,* 29**,** 362-391.

HOCK, R. & HOOKE, R. L. 1993. Evolution of the internal drainage system in the lower part of the ablation area of Storglaciaren, Sweden. Geological Society of America Bulletin, 105, 537-546.

HODGKINS, R. 2001. Seasonal evolution of meltwater generation, storage and discharge at a non-temperate glacier in Svalbard. *Hydrological Processes,* 15**,** 441-460.

HODSON, A. J., GURNELL, A. M., WASHINGTON, R., TRANTER, M., CLARK, M. J. & HAGEN, J. O. 1998. Meteorological and runoff time-series characteristics in a small, high-Arctic glaciated basin, Svalbard. *Hydrological Processes,* 12**,** 509-526.

HOLLAND, D. M., THOMAS, R. H., DE YOUNG, B., RIBERGAARD, M. H. & LYBERTH, B. 2008. Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience,* 1**,** 659-664.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

JANSSENS, I. & HUYBRECHTS, P. 2000. The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet. *Annals of Glaciology, Vol 31, 2000,* 31**,** 133-140.

JANSSON, P., HOCK, R. & SCHNEIDER, T. 2003. The concept of glacier storage: a review. *Journal of Hydrology,* 282**,** 116-129.

JENSEN, H. AND LANG, H. 1973. Forecasting discharge from a glaciated basin in the Swiss Alps. In: Role of Snow and Ice in Hydrology (Proc. Banff Symposia, September 1972), vol. 2, 1047-1054. IAHS Publ. no. 107.

JOBARD, S. & DZIKOWSKI, M. 2006. Evolution of glacial flow and drainage during the ablation season. *Journal of Hydrology,* 330**,** 663-671.

JOUGHIN, I., HOWAT, I. M., FAHNESTOCK, M., SMITH, B., KRABILL, W., ALLEY, R. B., STERN, H. & TRUFFER, M. 2008. Continued evolution of Jakobshavn Isbrae following its rapid speedup. *Journal of Geophysical Research-Earth Surface,* 113.

KAMB B. 1987. Glacier surge mechanism based on linked cavity configuration of the basal conduit system. Journal of Geophysical Research, 92, 9083–9100.

KERN-HANSEN, C. 1988. Hydrological Background of a Glacier-Influenced Hydropower Station in Greenland. Nordic Hydrology Vol 19 No 4 pp 269–280

KRABILL, W., ABDALATI, W., FREDERICK, E., MANIZADE, S., MARTIN, C., SONNTAG, J., SWIFT, R., THOMAS, R., WRIGHT, W. & YUNGEL, J. 2000. Greenland ice sheet: High-elevation balance and peripheral thinning. *Science,* 289**,** 428-430.

LAFRENEIRE, M. & SHARP, M. 2003. Wavelet analysis of inter-annual variability in the runoff regimes of glacial and nival stream catchments, Bow Lake, Alberta. *Hydrological Processes,* 17**,** 1093-1118.

LAWLER, D. M., MCGREGOR, G. R. & PHILLIPS, I. D. 2003. Influence of atmospheric circulation changes and regional climate variability on river flow and suspended sediment fluxes in southern Iceland. Hydrological Processes, 17, 3195-3223.

LAWLER, D. M. & WRIGHT, L. J. 1999. The impact of recent climate change on river flow and glaciofluvial suspended sediment loads in south Iceland. Fluvial Processes and Environmental Change, 385-407.

LONG, S. M. 2008. Subglacial melt water drainage at Paakitsoq, West Greenland: insights from a distributed, physically based numerical model. Thesis (MPhil) University of Cambridge

MASLANIK, J. A., FOWLER, C., STROEVE, J., DROBOT, S., ZWALLY, J., YI, D. & EMERY, W. 2007. A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. *Geophysical Research Letters,* 34.

MOORE, R. D. & DEMUTH, M. N. 2001. Mass balance and streamflow variability at Place Glacier, Canada, in relation to recent climate fluctuations. *Hydrological Processes,* 15**,** 3473-3486.

MOTE, T. L., ANDERSON, M. R., KUIVINEN, K. C. & ROWE, C. M. 1993. Passive microwave-derived spatial and temporal variations of summer melt on the Greenland ice-sheet. *Annals of Glaciology, Vol 17***,** 233-238.

NGHIEM, S. V., STEFFEN, K., KWOK, R. & TSAI, W. Y. 2001. Detection of snowmelt regions on the Greenland ice sheet using diurnal backscatter change. *Journal of Glaciology,* 47**,** 539-547.

NIENOW, P., SHARP, M. & WILLIS, I. 1998. Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms,* 23**,** 825-843.

OERLEMANS, J., BJORNSSON, H., KUHN, M., OBLEITNER, F., PALSSON, F., SMEETS, C., VUGTS, H. F. & DE WOLDE, J. 1999. Glacio-meteorological investigations on Vatnajokull, Iceland, Summer 1996: An overview. *Boundary-Layer Meteorology,* 92**,** 3-26.

OSTLING, M. & HOOKE, R. L. 1986. Water storage in Storglaciaren, Kebnekaise, Sweden. Geografiska Annaler Series a-Physical Geography, 68, 279-290.

RICHARDS, K. 1984. Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. *Earth Surface Processes and Landforms,* 9**,** 101-112.

RICHARDS, K., SHARP, M., ARNOLD, N., GURNELL, A., CLARK, M., TRANTER, M., NIENOW, P., BROWN, G., WILLIS, I. & LAWSON, W. 1996. An integrated approach to modelling hydrology and water quality in glacierized catchments. *Hydrological Processes,* 10**,** 479-508.

RIGNOT, E. & KANAGARATNAM, P. 2006. Changes in the velocity structure of the Greenland ice sheet. *Science,* 311**,** 986-990.

SHEA, J. M., ANSLOW, F. S. & MARSHALL, S. J. 2005. Hydrometeorological relationships on Haig Glacier, Alberta, Canada. *Annals of Glaciology, Vol 40, 2005,* 40**,** 52-60.

SHEPHERD, A., HUBBARD, A., NIENOW, P., KING, M., MCMILLAN, M. & JOUGHIN, I. 2009. Greenland ice sheet motion coupled with daily melting in late summer. *Geophysical Research Letters,* 36.

SICART, J. E., HOCK, R. & SIX, D. 2008. Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden. *Journal of Geophysical Research-Atmospheres,* 113**,** 11.

SINGH, P., RAMASASTRI, K. S., KUMAR, N. & ARORA, N. 2000. Correlations between discharge and meteorological parameters and runoff forecasting from a highly glacierized Himalayan basin. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques,* 45**,** 637-652.

SINGH, P. AND SINGH V. P. 2001. Snow and Glacier Hydrology. Kluwer Academic Publishers, pp741.

STOTT, T. A. & GROVE, J. R. 2001. Short-term discharge and suspended sediment fluctuations in the proglacial Skeldal River, north-east Greenland. *Hydrological Processes,* 15**,** 407-423.

SWIFT, D. A., NIENOW, P. W., HOEY, T. B. & MAIR, D. W. F. 2005. Seasonal evolution of runoff from Haut Glacier d'Arolla, Switzerland and implications for glacial geomorphic processes. *Journal of Hydrology,* 309**,** 133-148.

TANGBORN, W. V. & RASMUSSEN, L. A. 1976. Hydrology of North Cascades Region, Washington .2. proposed hydrometeorological streamflow prediction method. *Water Resources Research,* 12**,** 203-216.

THOMSEN, H., L. THORNING AND R. BRAITHWAITE. 1988. Glacier-hydrological conditions on the Inland Ice Northeast of Jakobshavn/Ilulissat, West Greenland. Grønlands Geologiske Undersøgelse. Rapport 138.

VAN DE WAL, R. S. W., BOOT, W., VAN DEN BROEKE, M. R., SMEETS, C., REIJMER, C. H., DONKER, J. J. A. & OERLEMANS, J. 2008. Large and rapid melt-induced velocity changes in the ablation zone of the Greenland Ice Sheet. *Science,* 321**,** 111-113.

WANG, L., SHARP, M., RIVARD, B. & STEFFEN, K. 2007. Melt season duration and ice layer formation on the Greenland ice sheet, 2000-2004. *Journal of Geophysical Research-Earth Surface,* 112.

WEIDICK, A. 1968. Observations on some Holocene glacier fluctuations in West Greenland. Meddeleser om Gronland, 165 (6), 202.

WILLIS, I. C., ARNOLD, N. S. & BROCK, B. W. 2002. Effect of snowpack removal on energy balance, melt and runoff in a small supraglacial catchment. *Hydrological Processes,* 16**,** 2721-2749.

WILLIS, I. & BONVIN, J. M. 1995. Climate-change in mountain environments - hydrological and water-resource implications. *Geography,* 80**,** 247-261.

WILLIS, I. C., RICHARDS, K. S. & SHARP, M. J. 1996. Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway. *Hydrological Processes,* 10**,** 629-648.

WILLIS, I.C. 2005. Hydrology *of Glacierised Basins*. In Anderson, M.G. (Ed). Encyclopedia of Hydrological Sciences. Wiley. Volume 4, Chapter 168, 2601-2631.

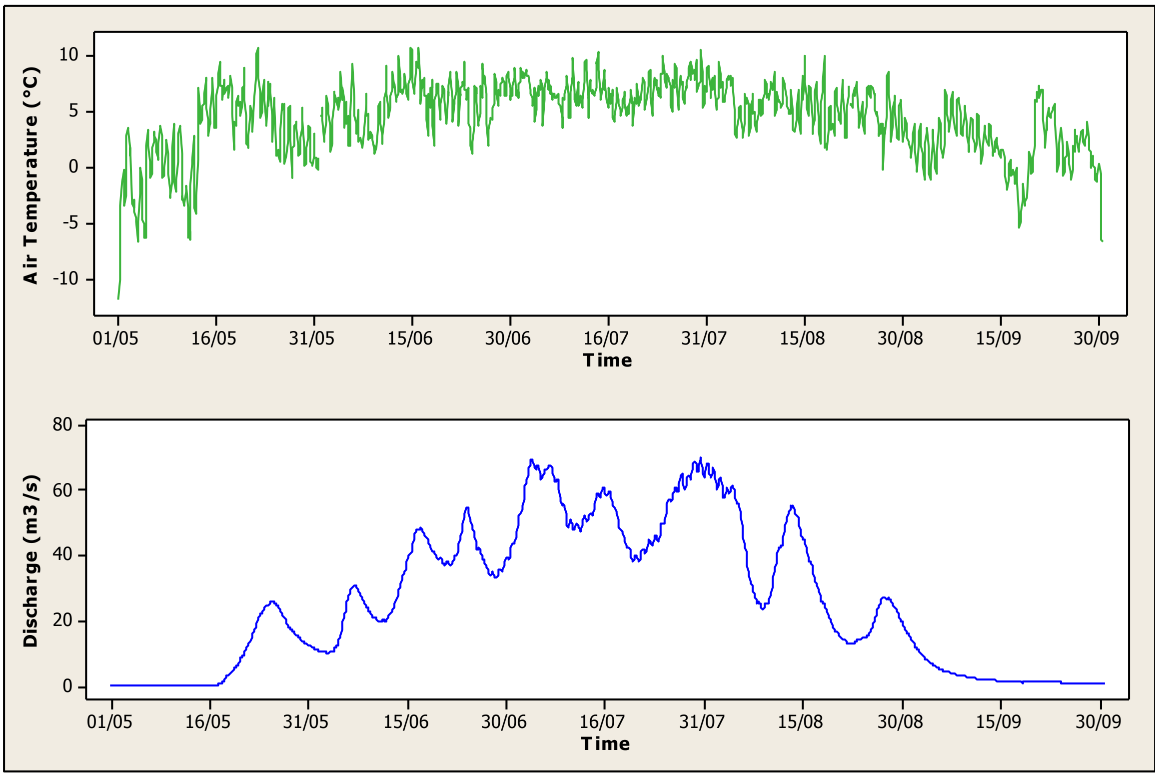
WOLFE, P. M. & ENGLISH, M. C. 1995a. Hydrometeorological relationships in a glacierized catchment in the Canadian high Arctic. *Hydrological Processes,* 9**,** 911-921.

WOLFE, P. M. & ENGLISH, M. C. 1995b. Hydrometeorological relationships in a glacierized catchment in the Canadian high arctic. *Proceedings of the Fifty-Second Annual Eastern Snow Conference***,** 163-173.

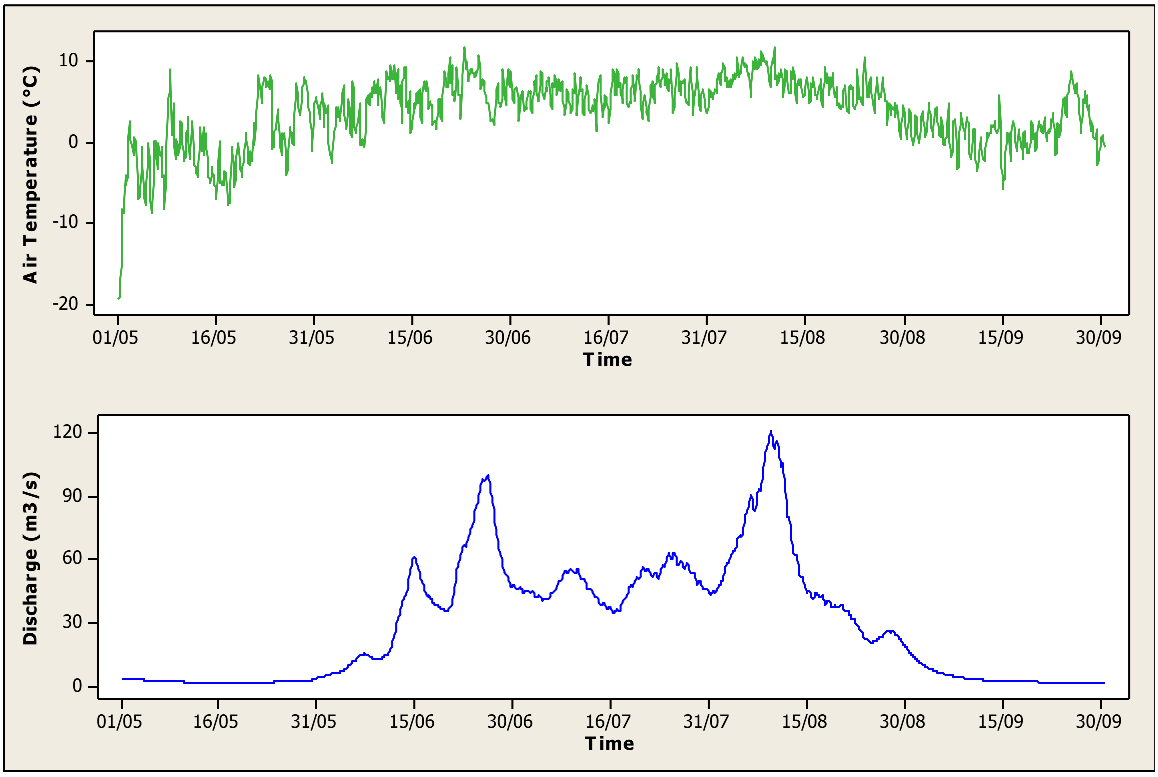
ZWALLY, H. J., ABDALATI, W., HERRING, T., LARSON, K., SABA, J. & STEFFEN, K. 2002. Surface melt-induced acceleration of Greenland ice-sheet flow. *Science,* 297**,** 218-222.

Appendix 1

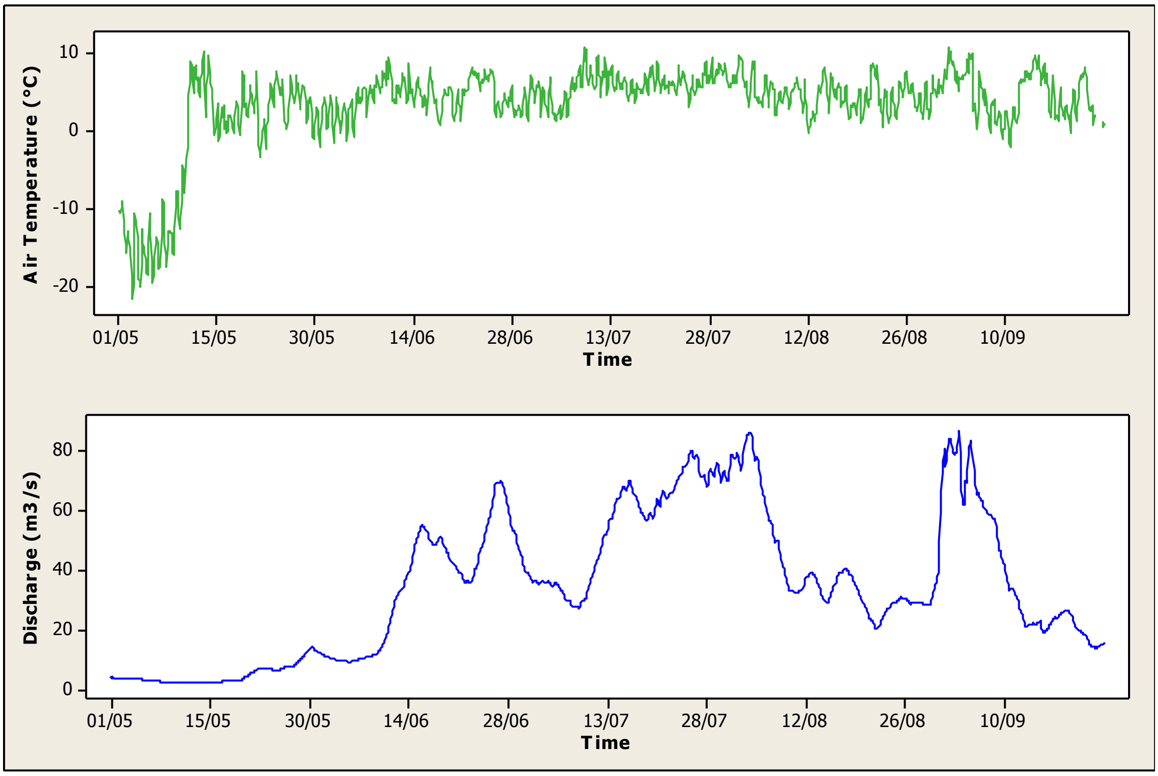
1985



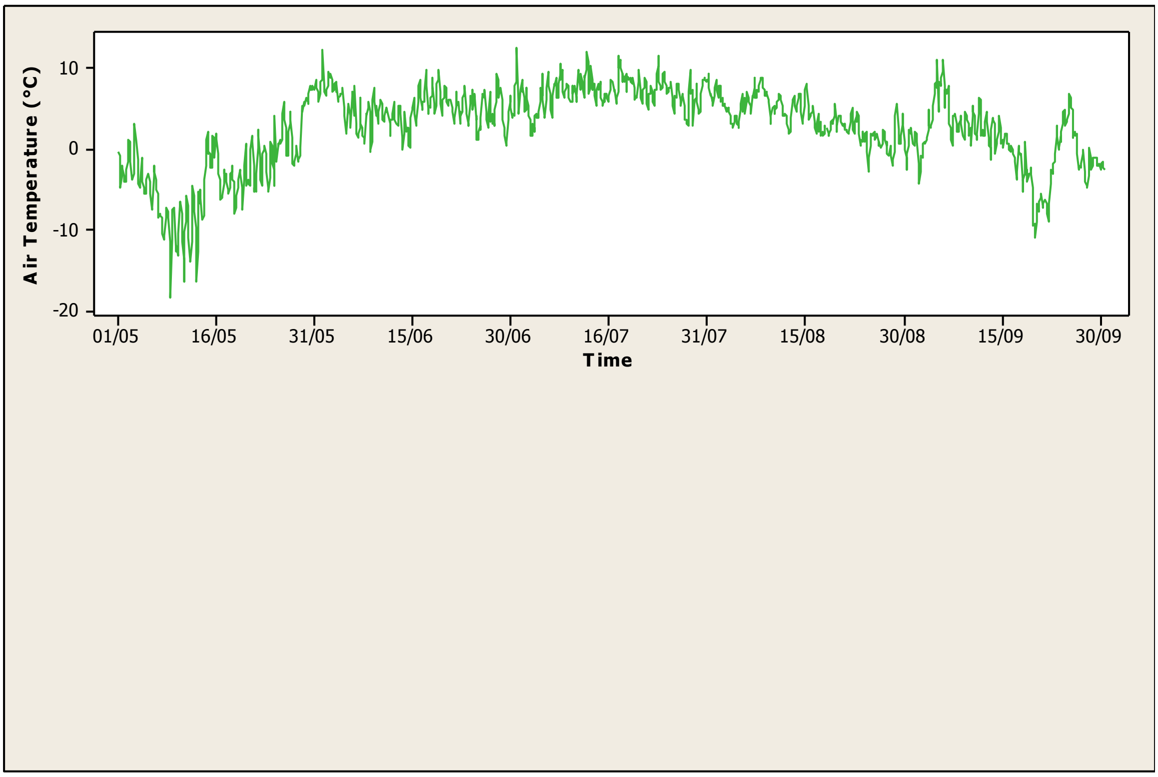
1987



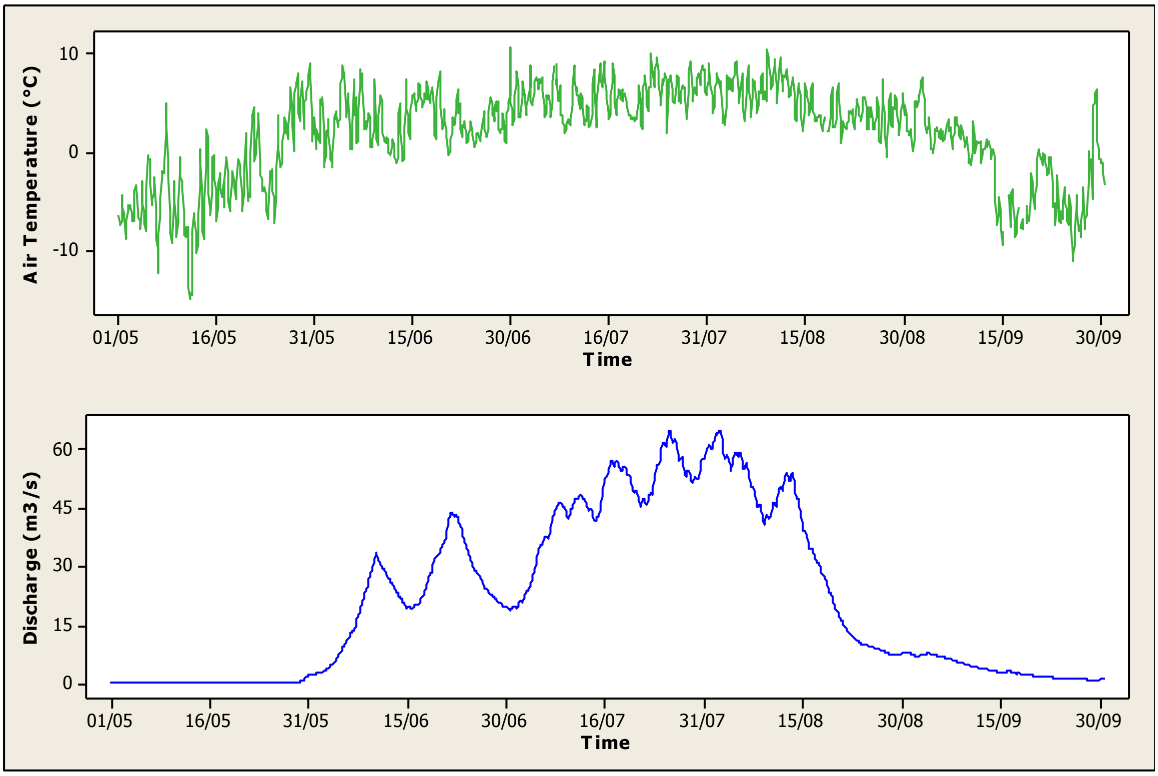
1989


Air Temperature (°C)
10
0
-10
-20
01/05
15/05
30/05
14/06
28/06
13/07
28/07
12/08
26/08
10/09
Time
Discharge (m3/s)
80
60
40
20
0
01/05
15/05
30/05
14/06
28/06
13/07
28/07
12/08
26/08
10/09
Time

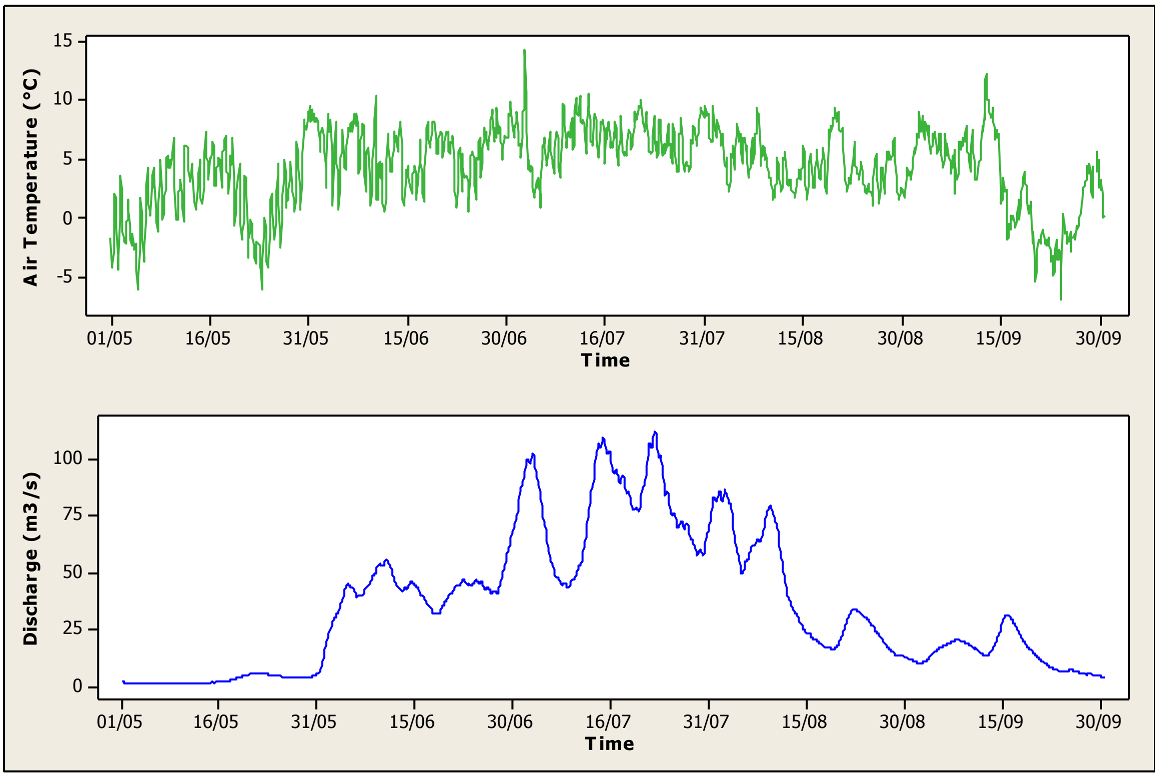
1991


Air Temperature (°C)
10
0
-10
-20
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

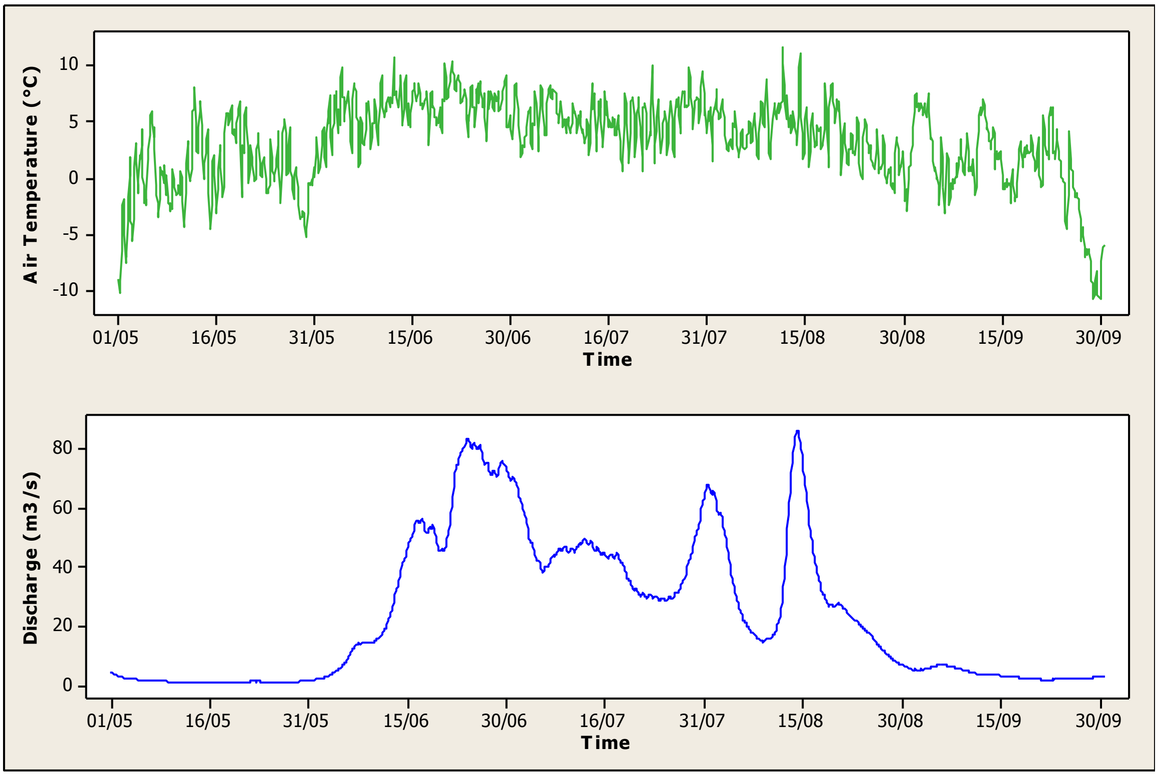
1993


Air Temperature (°C)
10
0
-10
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
60
45
30
15
0
Time

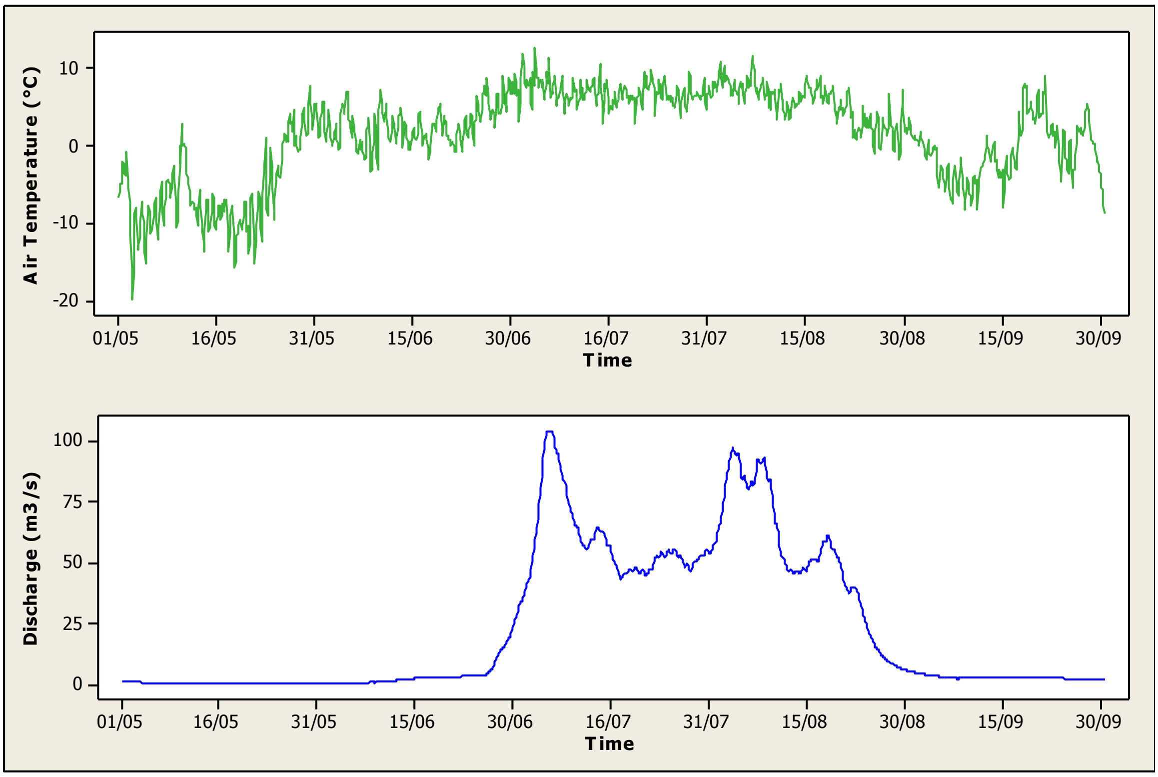
1995


Air Temperature (°C)
15
10
5
0
-5
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
100
75
50
25
0
Time

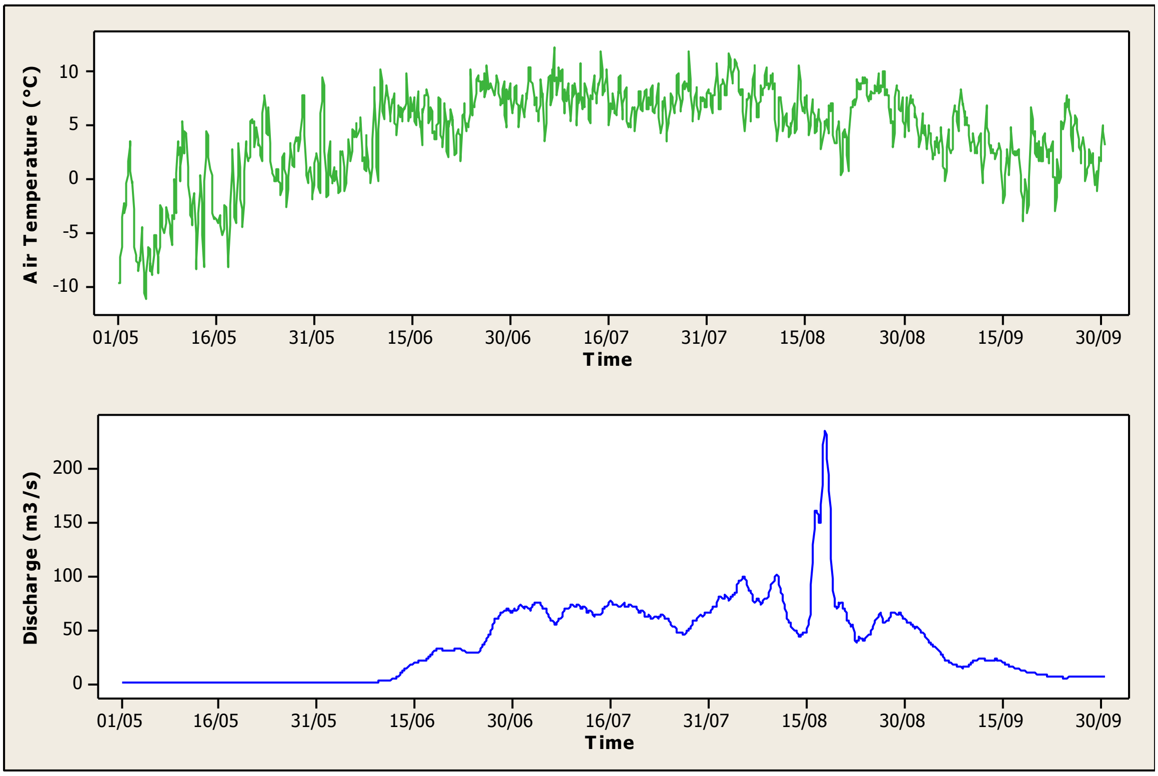
1997


Air Temperature (°C)
10
5
0
-5
-10
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
80
60
40
20
0
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

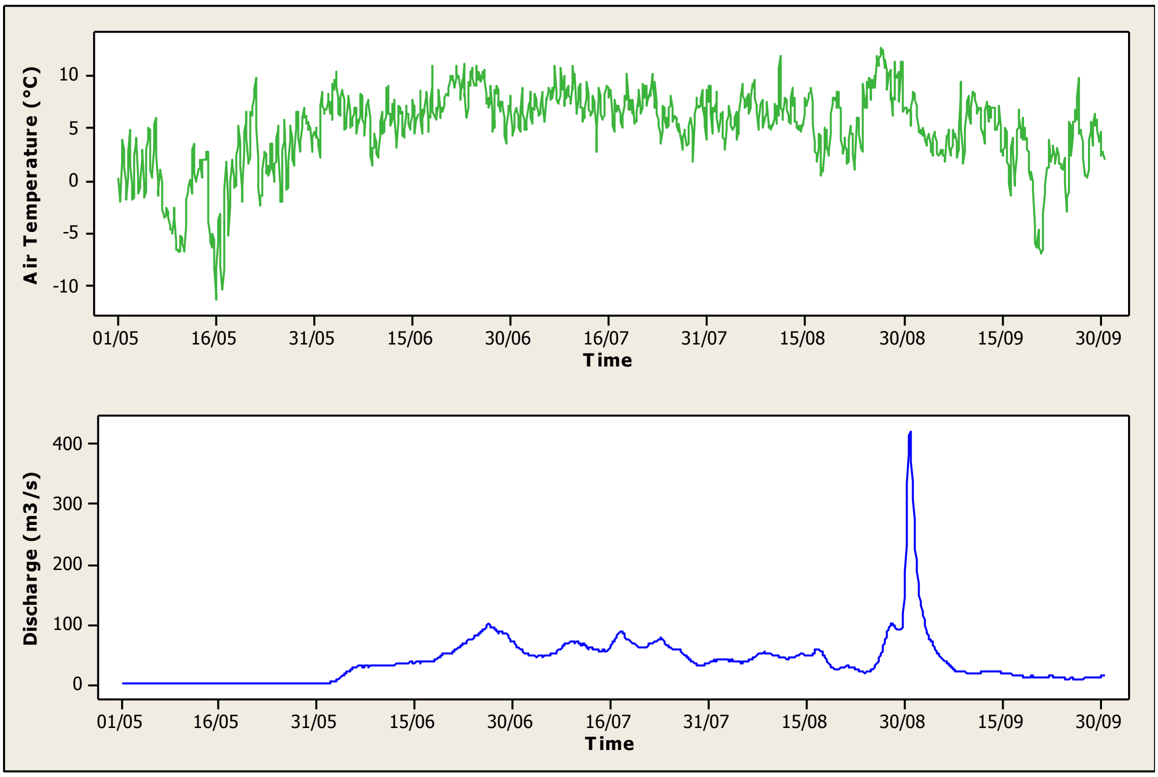
1999


Air Temperature (°C)
10
0
-10
-20
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
100
75
50
25
0
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

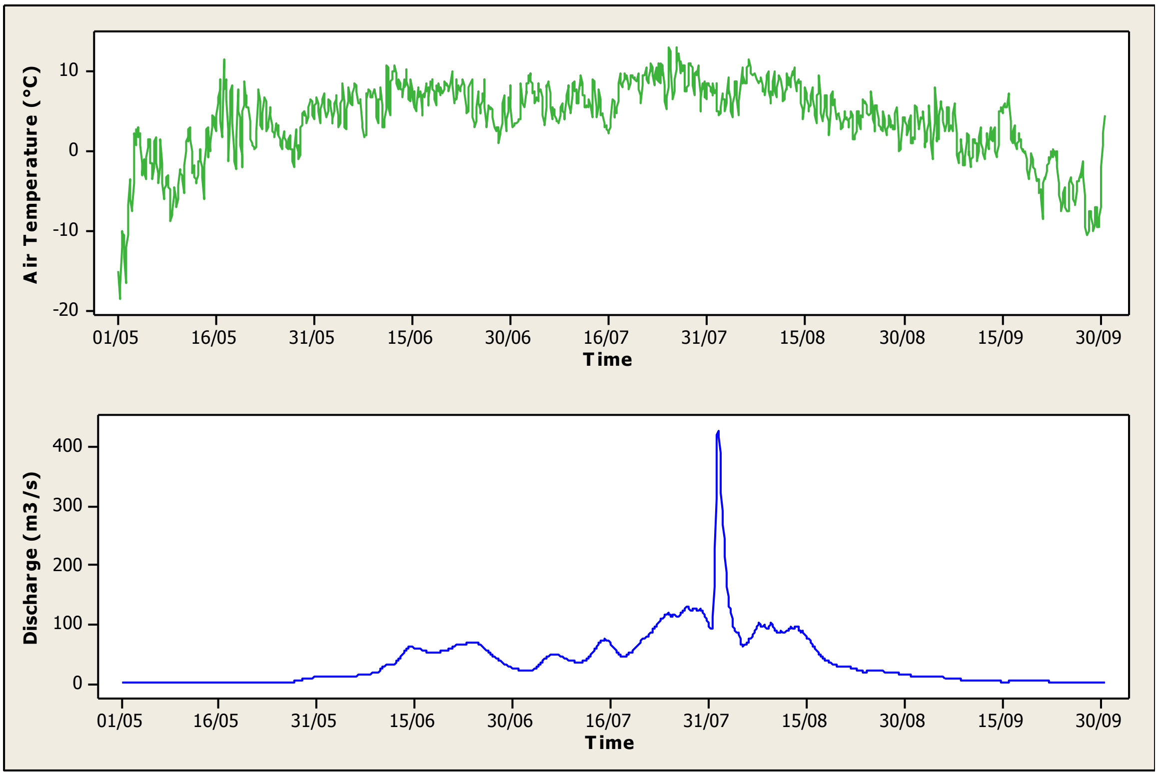
2001


Air Temperature (°C)
10
5
0
-5
-10
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
200
150
100
50
0
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

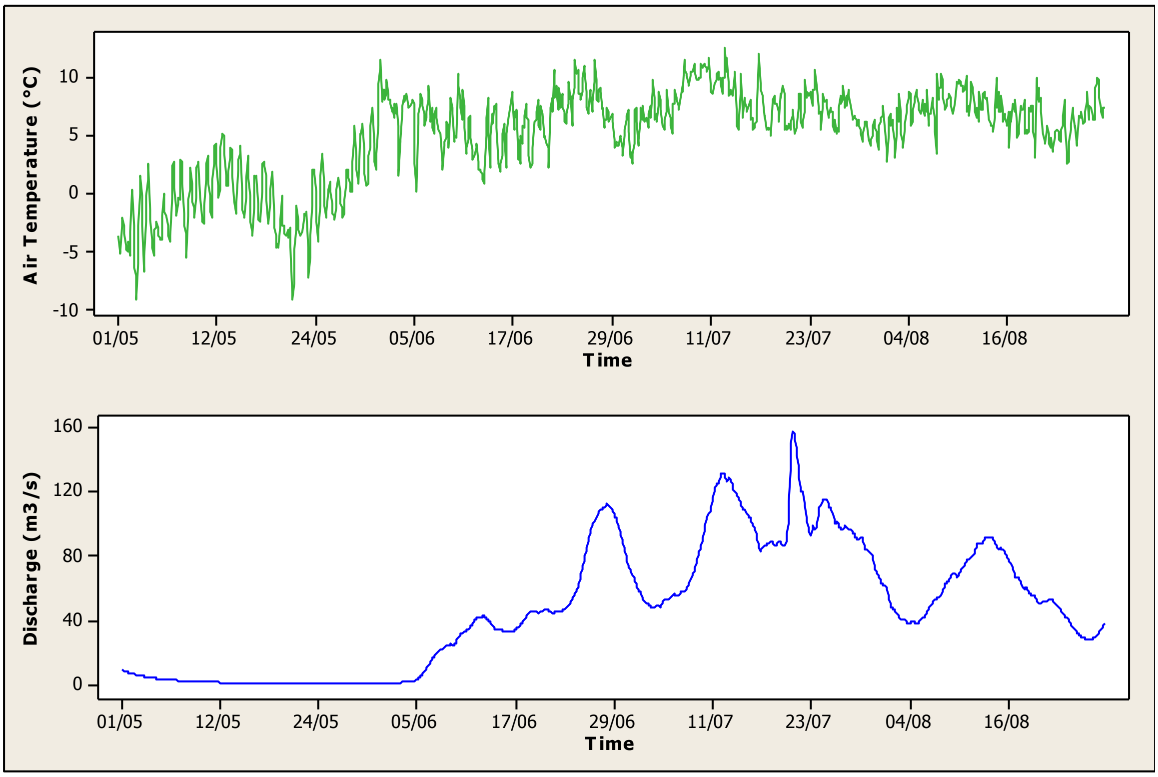
2003


Air Temperature (°C)
10
5
0
-5
-10
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
400
300
200
100
0
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

2005

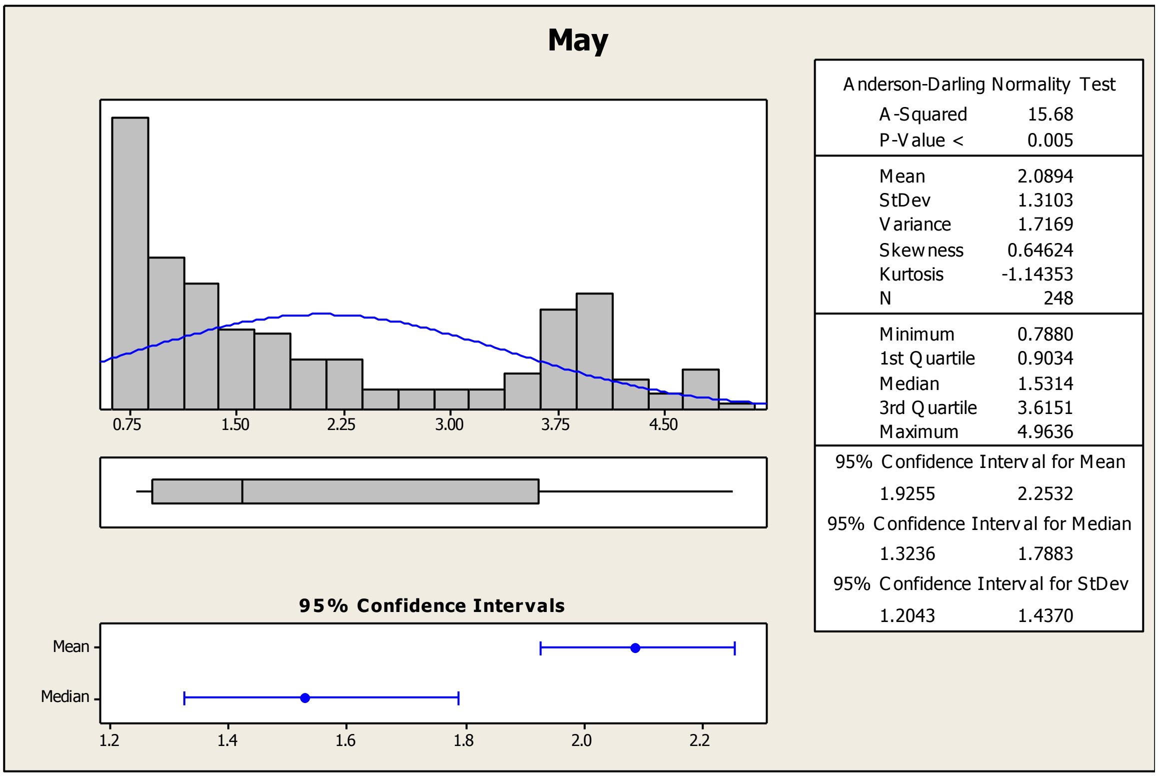

Air Temperature (°C)
10
0
-10
-20
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time
Discharge (m3/s)
400
300
200
100
0
01/05
16/05
31/05
15/06
30/06
16/07
31/07
15/08
30/08
15/09
30/09
Time

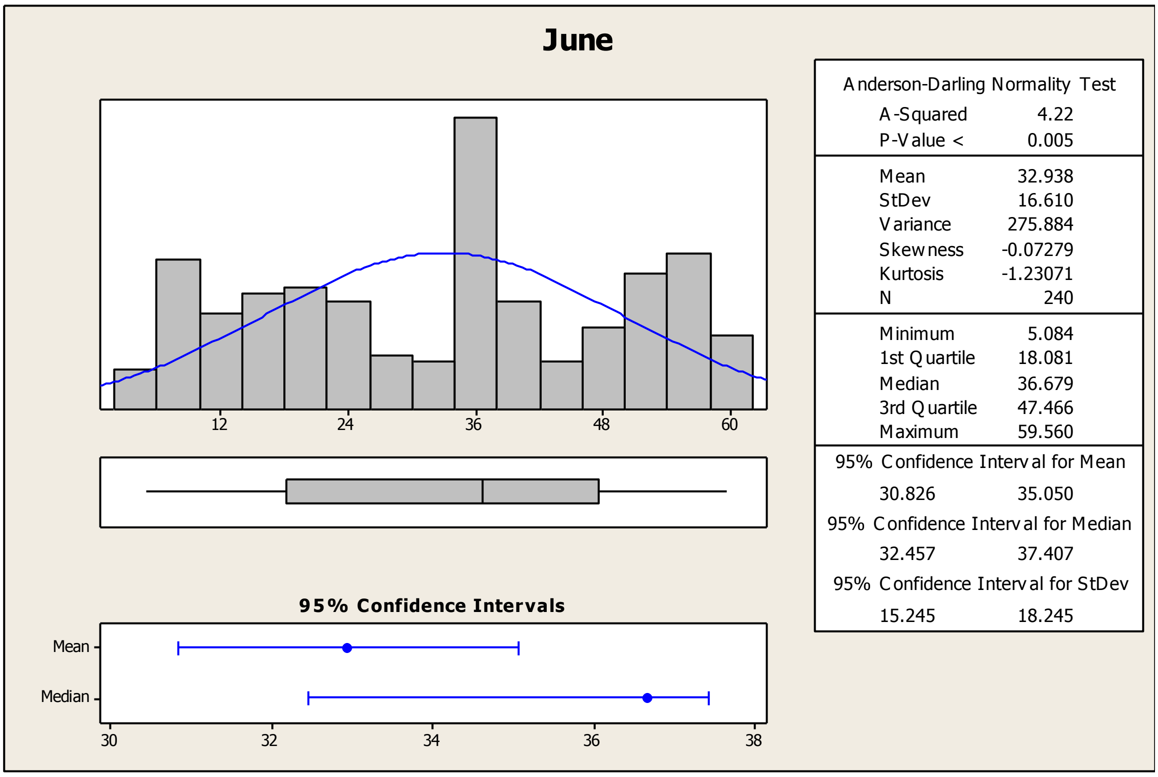
2007


Air Temperature (°C)
10
5
0
-5
-10
01/05
12/05
24/05
05/06
17/06
29/06
11/07
23/07
04/08
16/08
Time
Discharge (m3/s)
160
120
80
40
0
01/05
12/05
24/05
05/06
17/06
29/06
11/07
23/07
04/08
16/08
Time

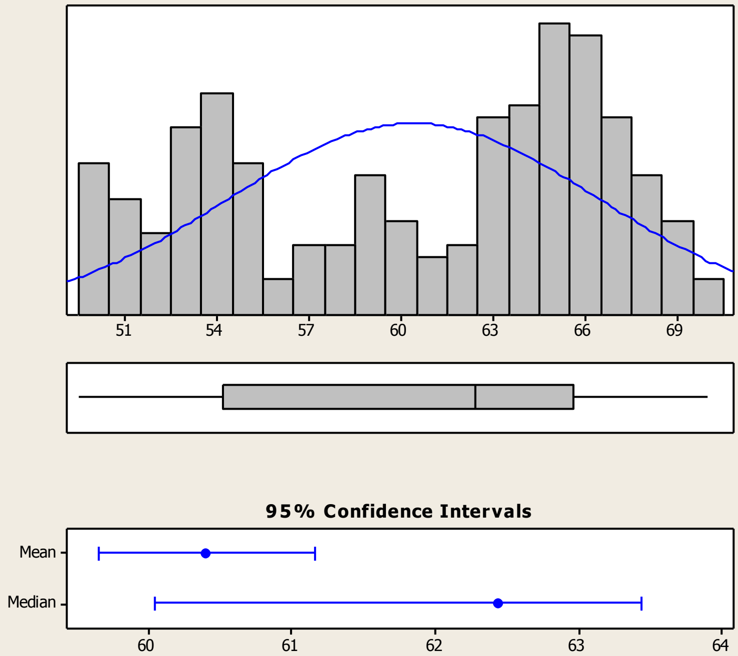
Appendix 2

Discharge



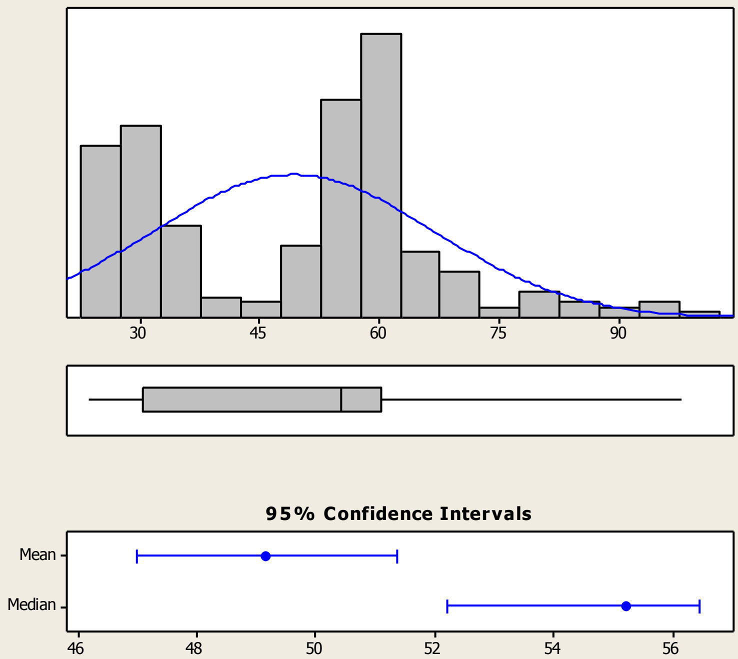


July

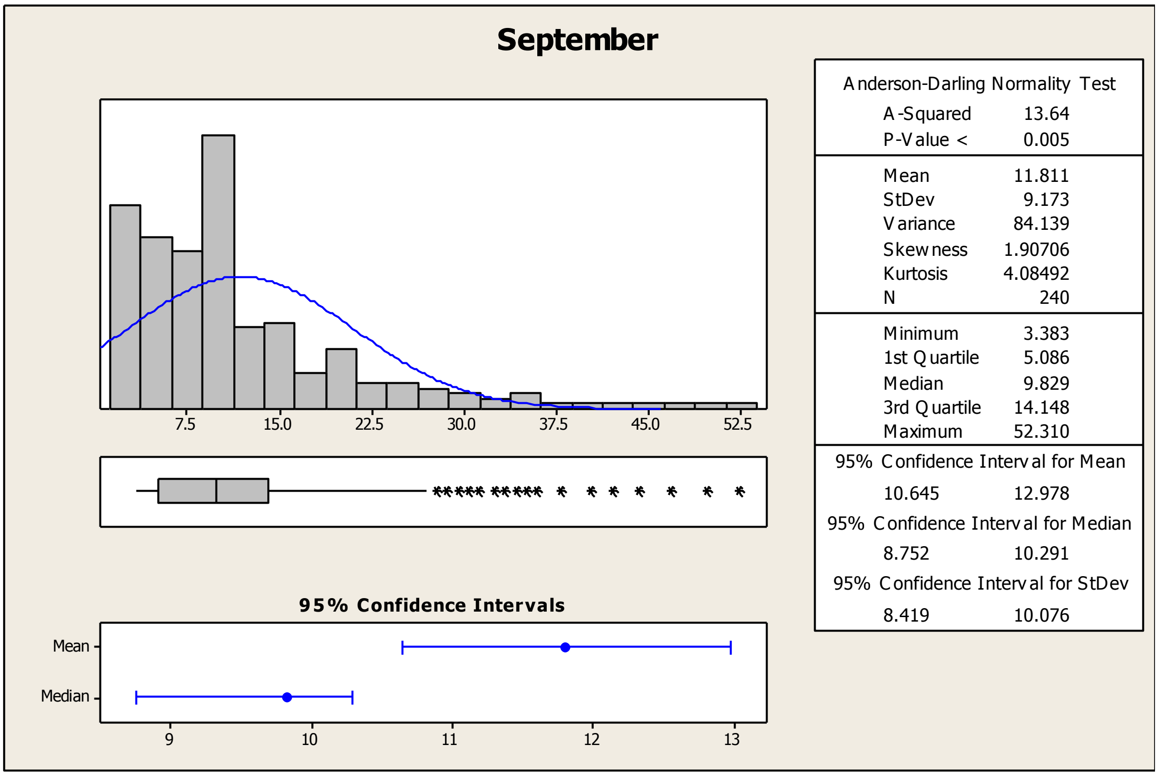


Anderson-Darling Normality Test	
A-Squared	7.80
P-Value <	0.005
Mean	60.409
StDev	6.025
Variance	36.304
Skewness	-0.32317
Kurtosis	-1.31980
N	248
Minimum	49.509
1st Quartile	54.195
Median	62.441
3rd Quartile	65.625
Maximum	69.973
95% Confidence Interval for Mean	
59.655	61.163
95% Confidence Interval for Median	
60.038	63.440
95% Confidence Interval for StDev	
5.538	6.608

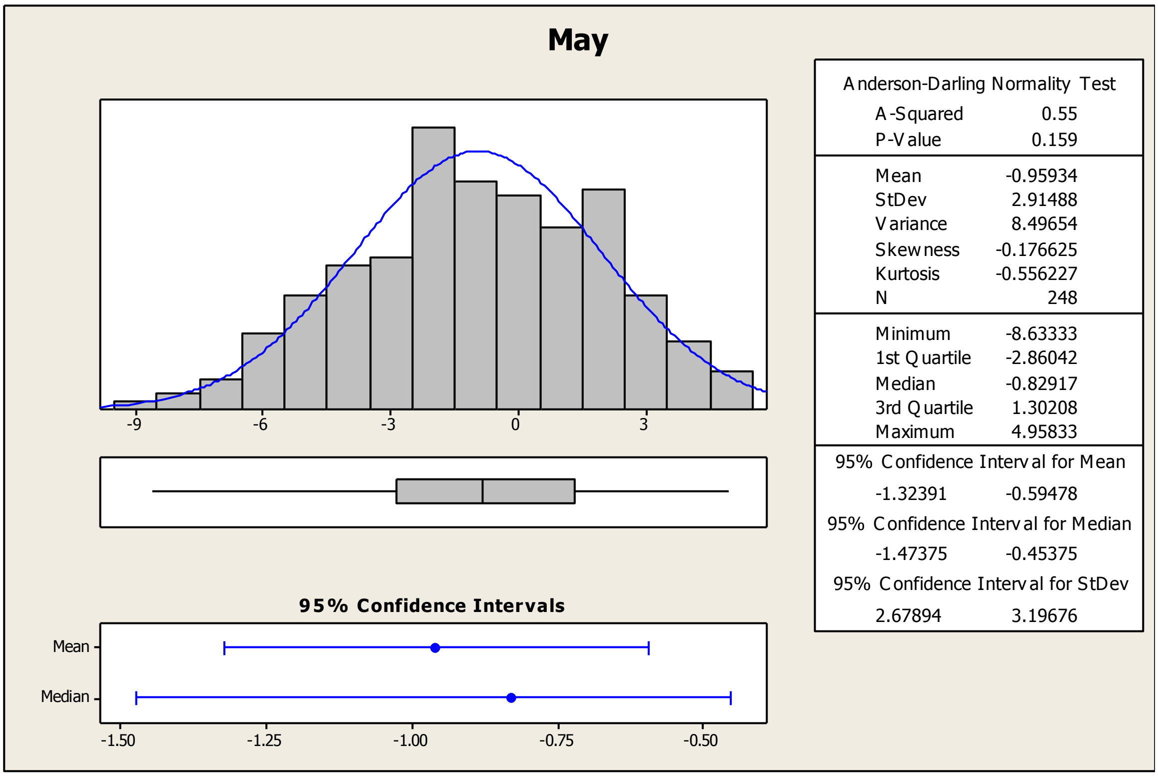
August



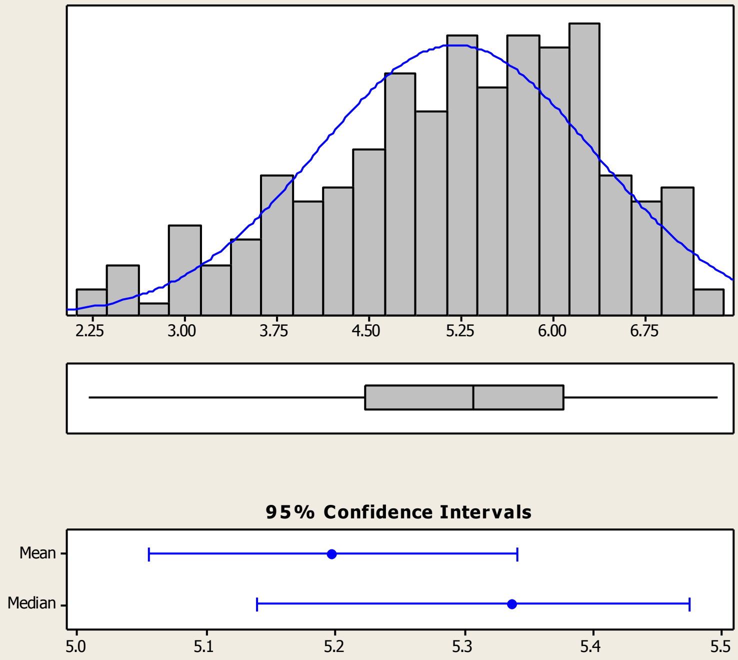
Anderson-Darling Normality Test	
A-Squared	8.96
P-Value <	0.005
Mean	49.186
StDev	17.536
Variance	307.504
Skewness	0.209400
Kurtosis	-0.522617
N	248
Minimum	23.541
1st Quartile	30.281
Median	55.223
3rd Quartile	60.061
Maximum	97.573
95% Confidence Interval for Mean	
46.993	51.379
95% Confidence Interval for Median	
52.214	56.452
95% Confidence Interval for StDev	
16.116	19.232



Air Temperature

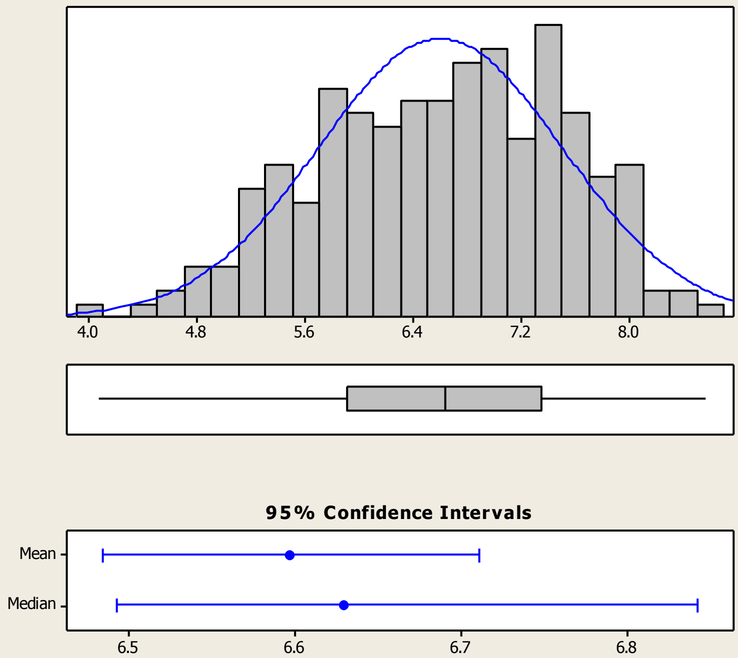


June

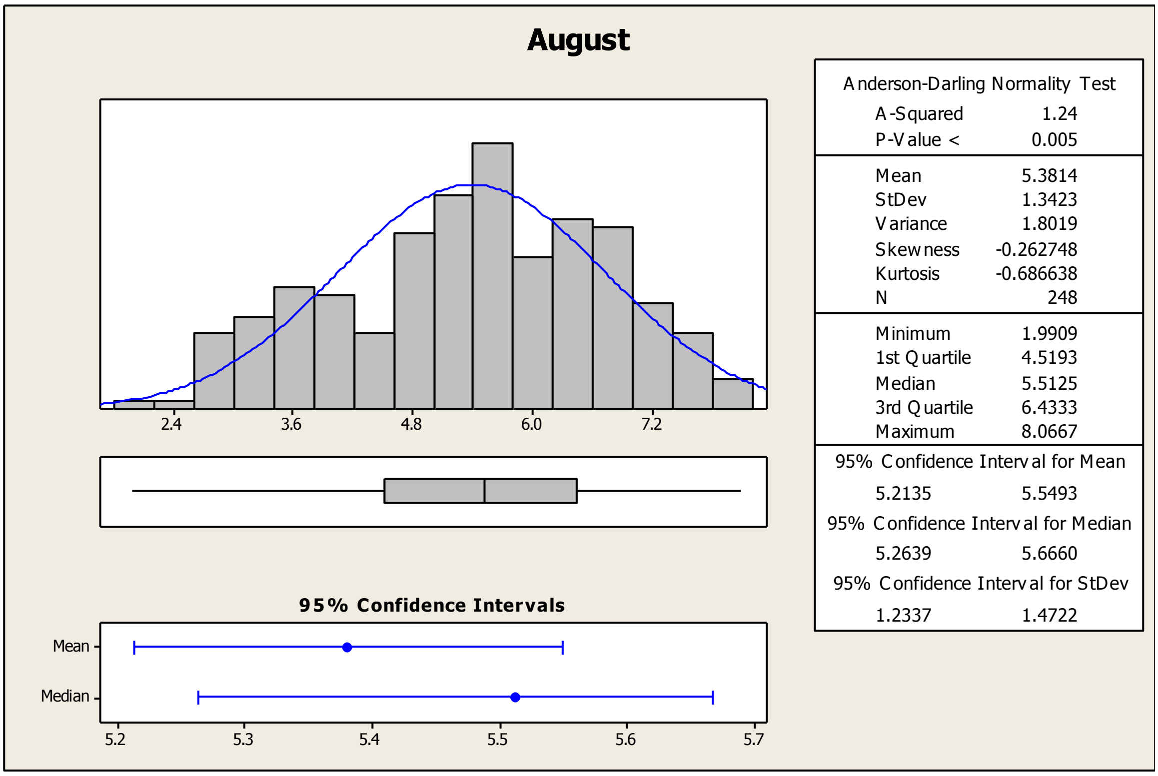


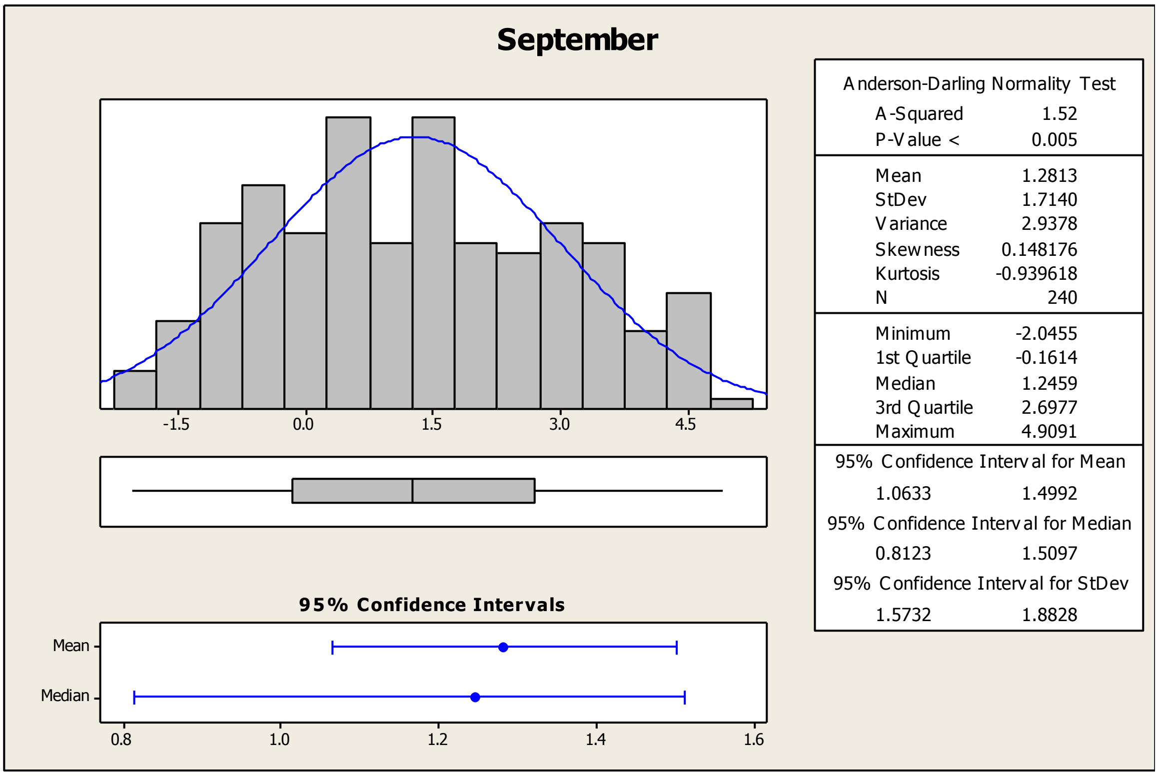
Anderson-Darling Normality Test	
A-Squared	1.62
P-Value <	0.005
Mean	5.1977
StDev	1.1253
Variance	1.2663
Skewness	-0.502877
Kurtosis	-0.302882
N	240
Minimum	2.2167
1st Quartile	4.4583
Median	5.3375
3rd Quartile	6.0729
Maximum	7.3250
95% Confidence Interval for Mean	
5.0546	5.3407
95% Confidence Interval for Median	
5.1391	5.4750
95% Confidence Interval for StDev	
1.0328	1.2361

July



Anderson-Darling Normality Test	
A-Squared	1.07
P-Value	0.008
Mean	6.5970
StDev	0.9049
Variance	0.8189
Skewness	-0.238182
Kurtosis	-0.604473
N	248
Minimum	4.0667
1st Quartile	5.9083
Median	6.6292
3rd Quartile	7.3396
Maximum	8.5667
95% Confidence Interval for Mean	
6.4838	6.7102
95% Confidence Interval for Median	
6.4923	6.8417
95% Confidence Interval for StDev	
0.8317	0.9924

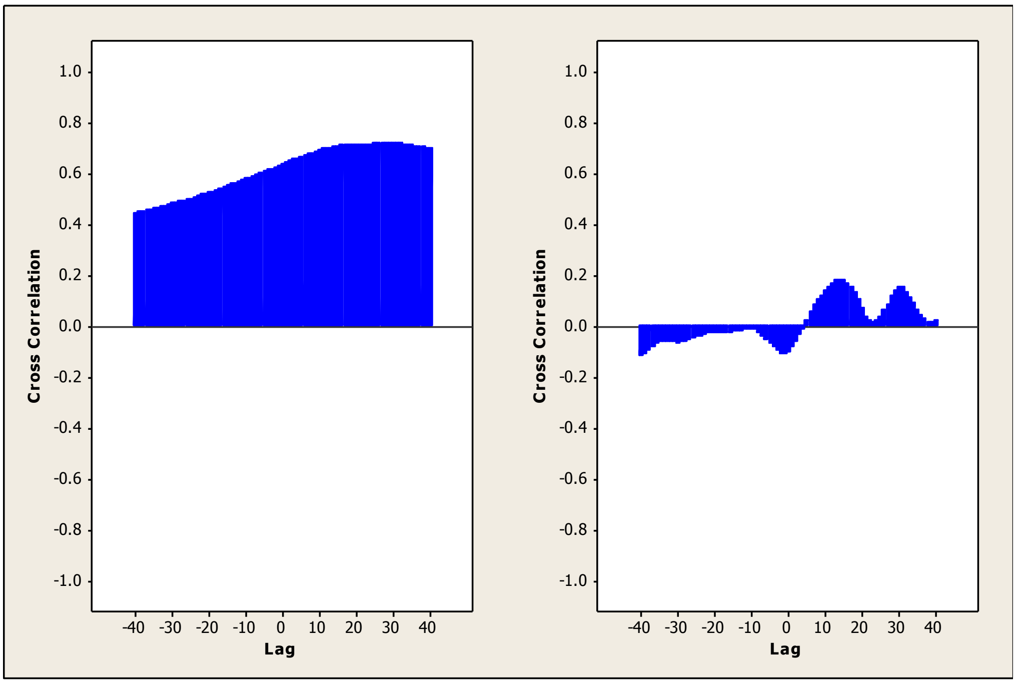

August
Anderson-Darling Normality Test
A-Squared 1.24
P-Value < 0.005
Mean 5.3814
StDev 1.3423
Variance 1.8019
Skewness -0.262748
Kurtosis -0.686638
N 248
Minimum 1.9909
1st Quartile 4.5193
Median 5.5125
3rd Quartile 6.4333
Maximum 8.0667
95% Confidence Interval for Mean
5.2135 5.5493
95% Confidence Interval for Median
5.2639 5.6660
95% Confidence Interval for StDev
1.2337 1.4722
2.4 3.6 4.8 6.0 7.2
95% Confidence Intervals
Mean
Median
5.2 5.3 5.4 5.5 5.6 5.7


September
Anderson-Darling Normality Test
A-Squared 1.52
P-Value < 0.005
Mean 1.2813
StDev 1.7140
Variance 2.9378
Skewness 0.148176
Kurtosis -0.939618
N 240
Minimum -2.0455
1st Quartile -0.1614
Median 1.2459
3rd Quartile 2.6977
Maximum 4.9091
95% Confidence Interval for Mean
1.0633 1.4992
95% Confidence Interval for Median
0.8123 1.5097
95% Confidence Interval for StDev
1.5732 1.8828
-1.5 0.0 1.5 3.0 4.5
95% Confidence Intervals
Mean
Median
0.8 1.0 1.2 1.4 1.6

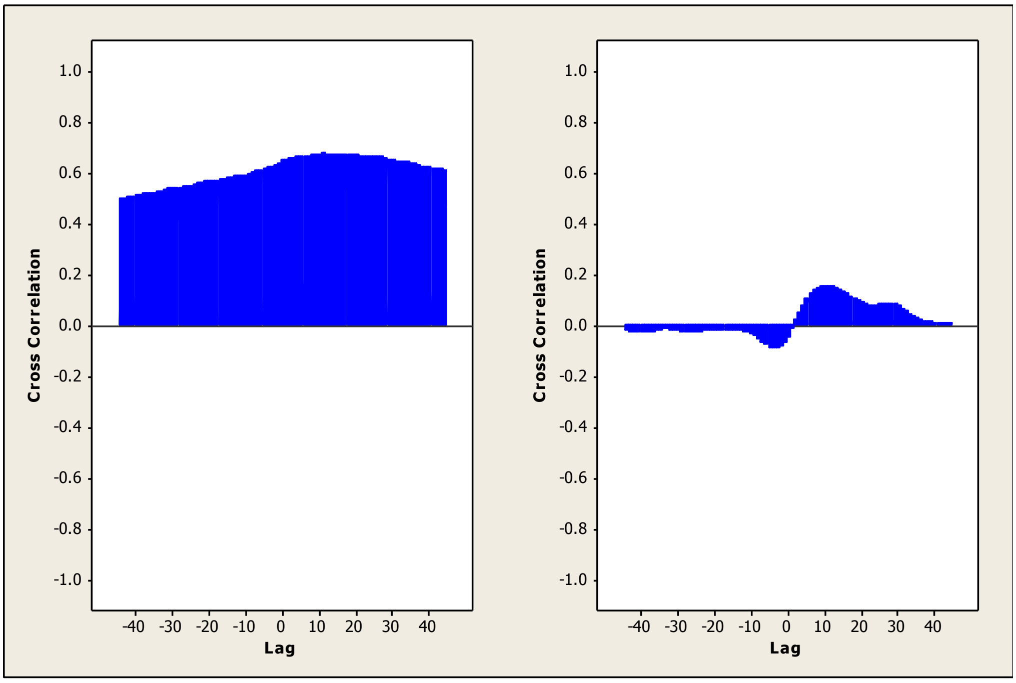
Appendix 3

Seasonal Cross Correlation Plots. For each year, the left plot represents raw data and the right one represents seasonally differenced data. The lags represent intervals of 3 hours. For example a lag of 3 represents a lag of 9 hours.

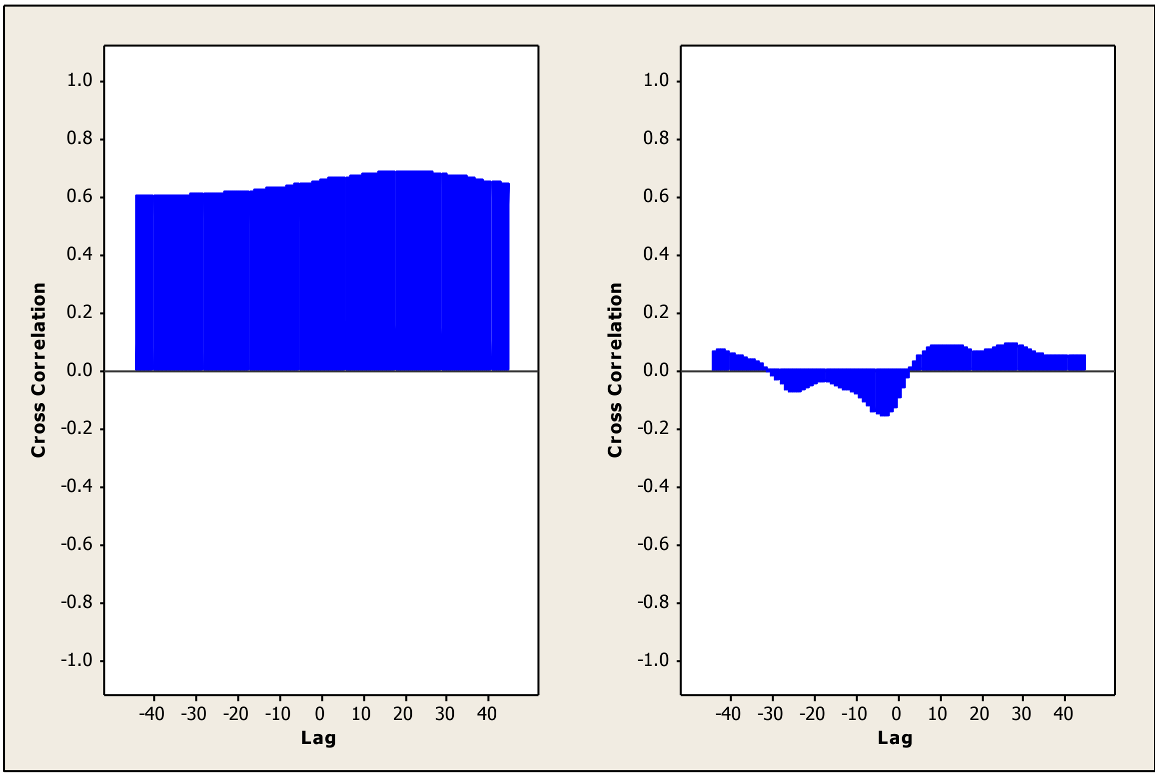
1985



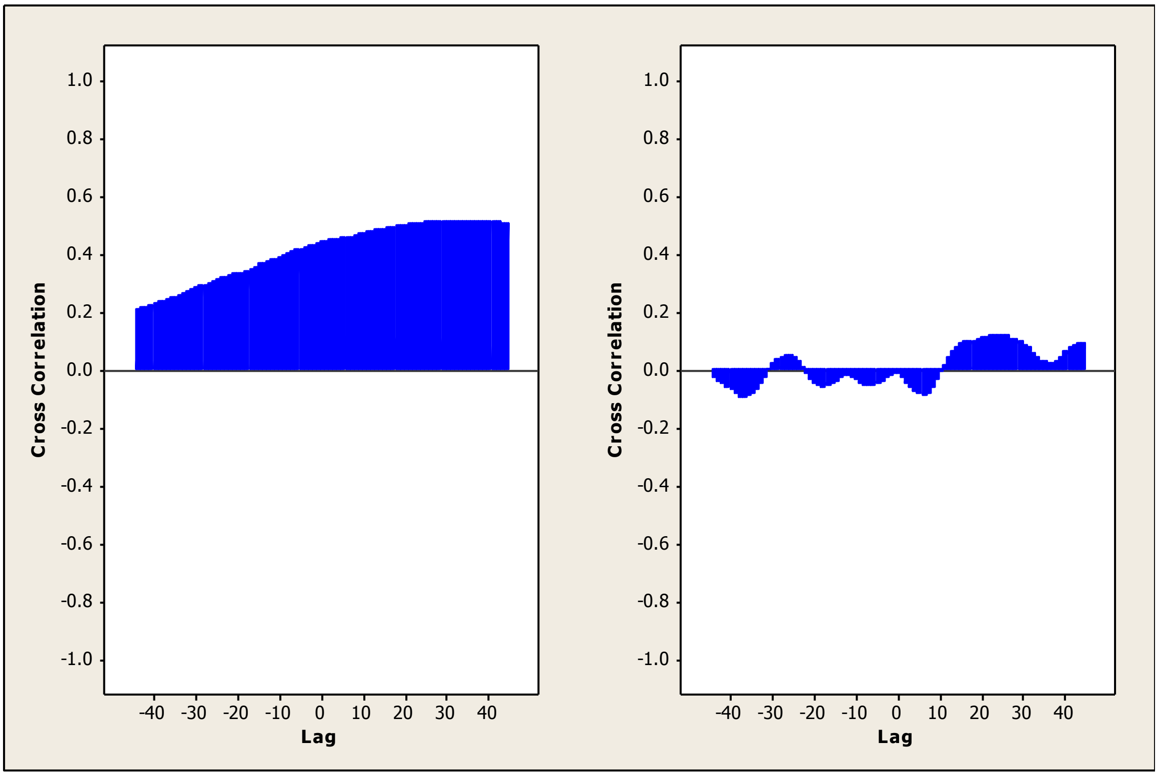
1987



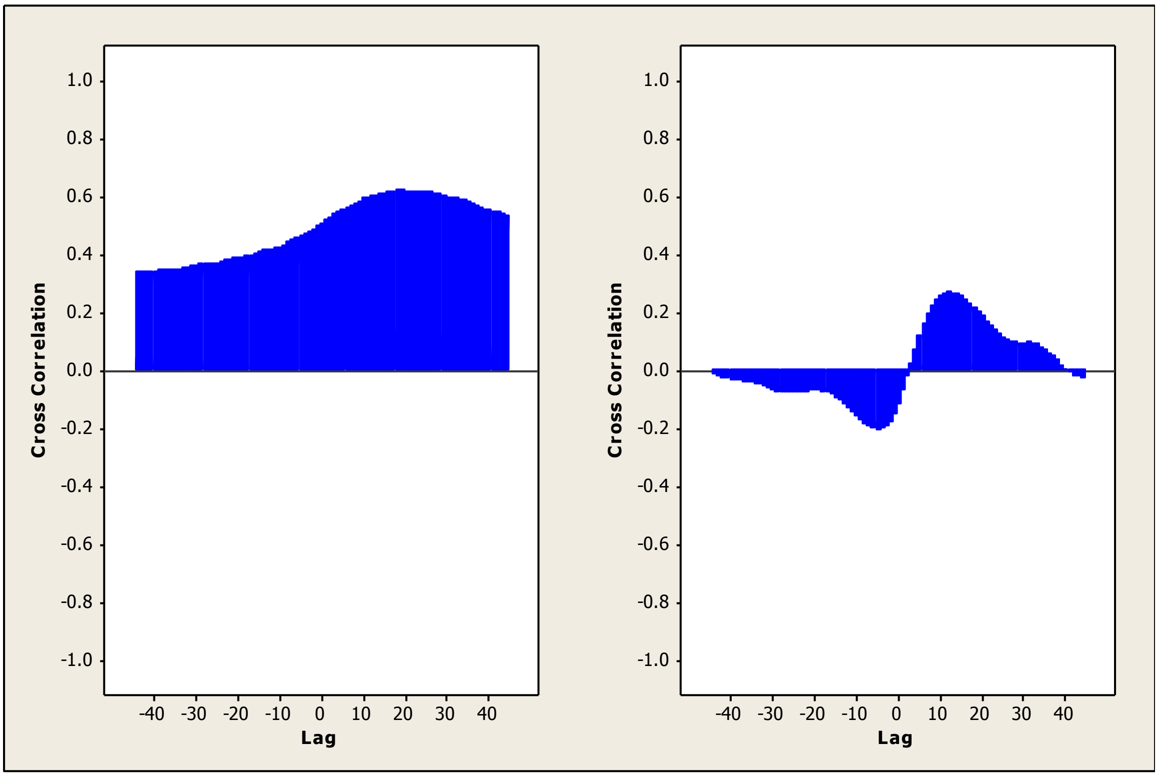
1989


Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

1993

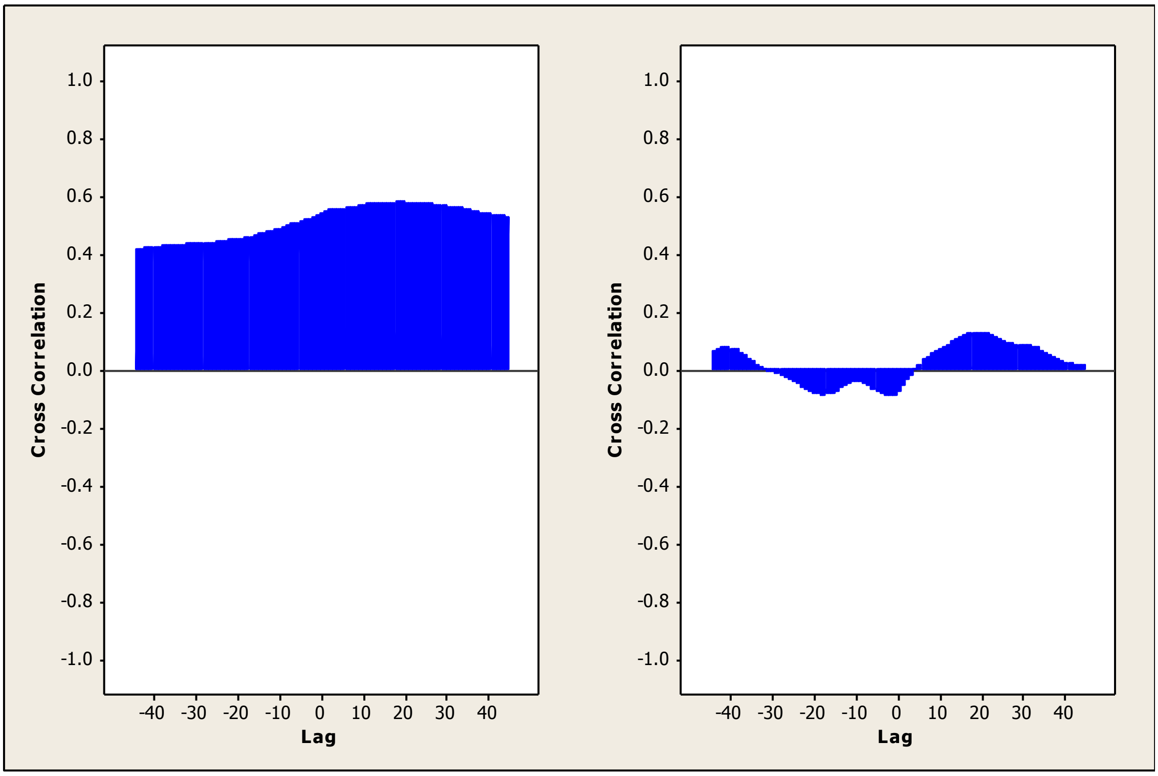

Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

1995



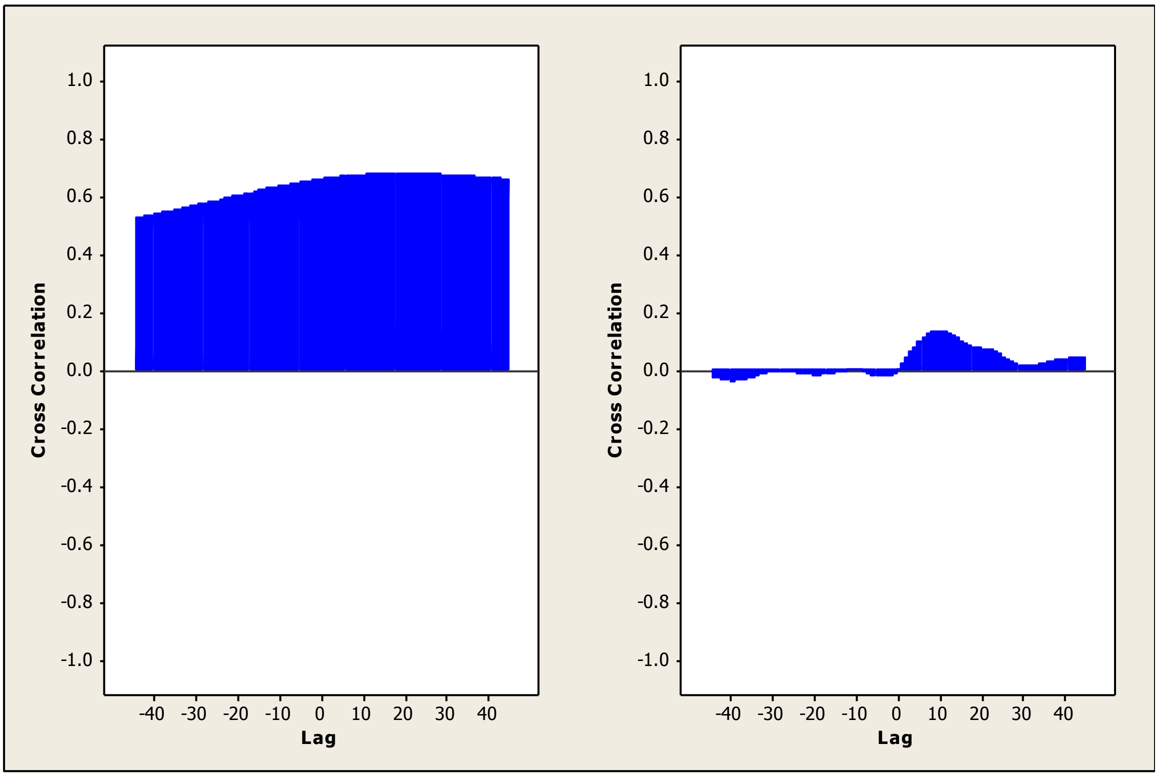
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

1997



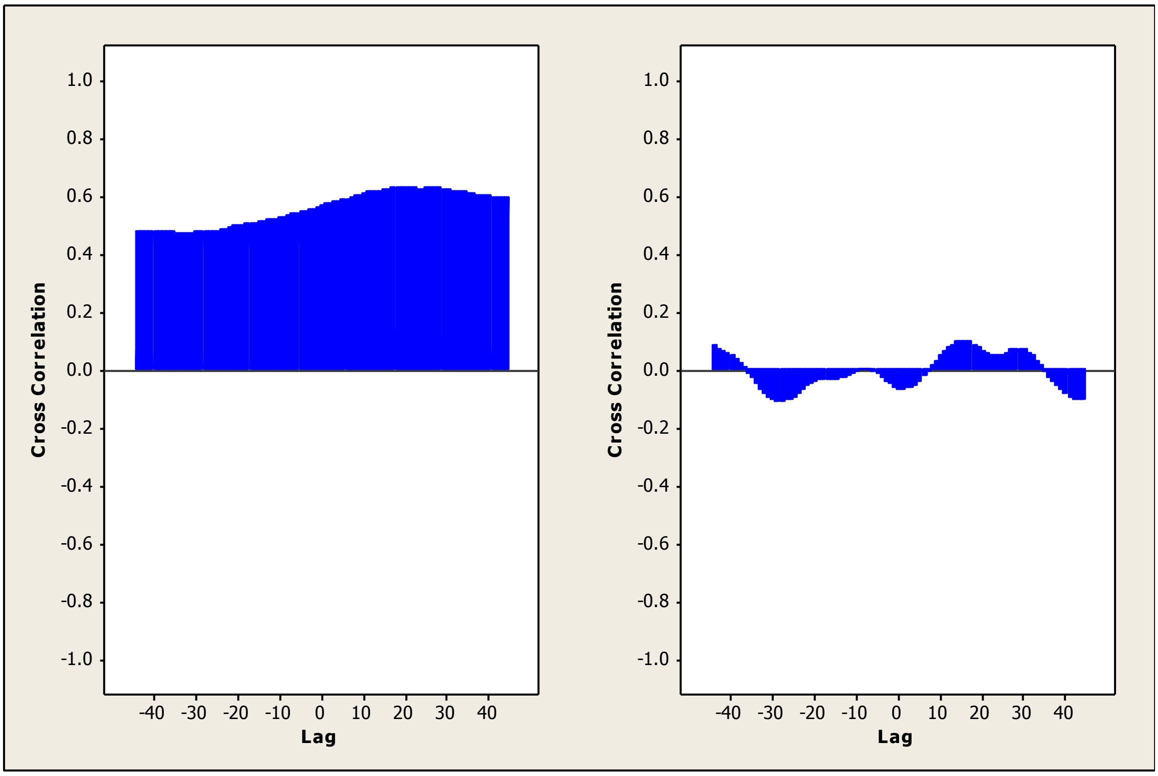
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

1999



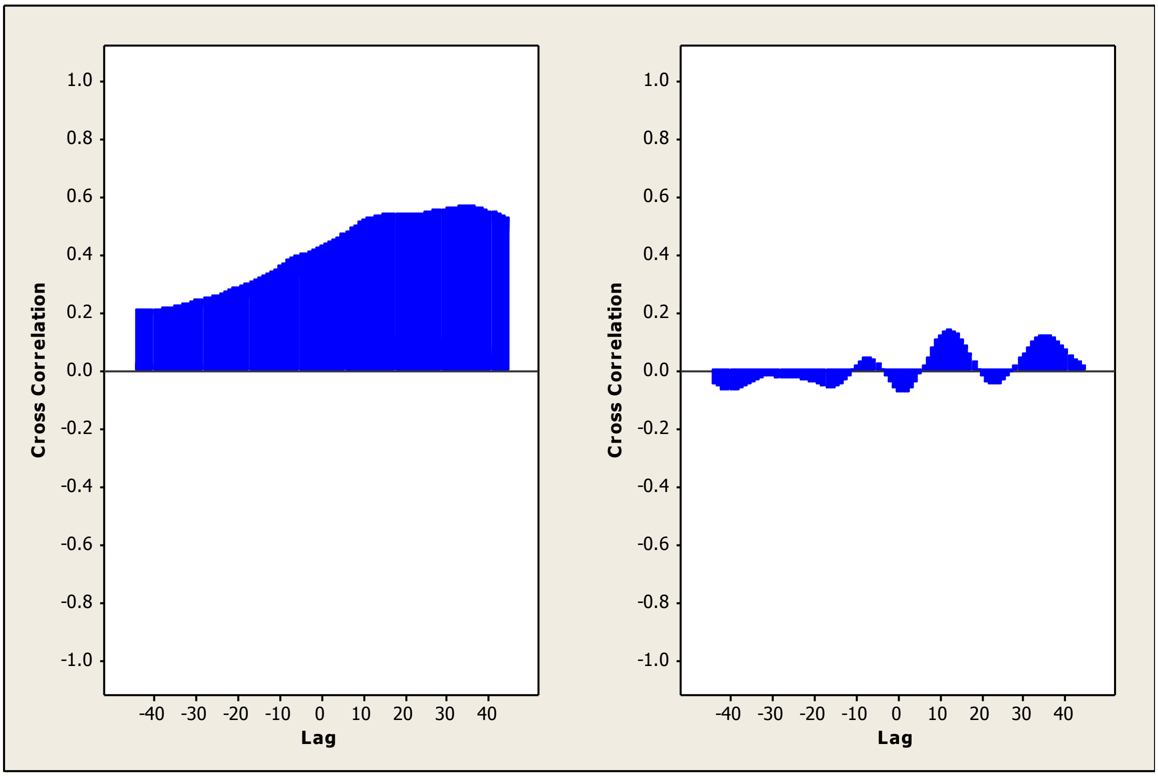
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

2001



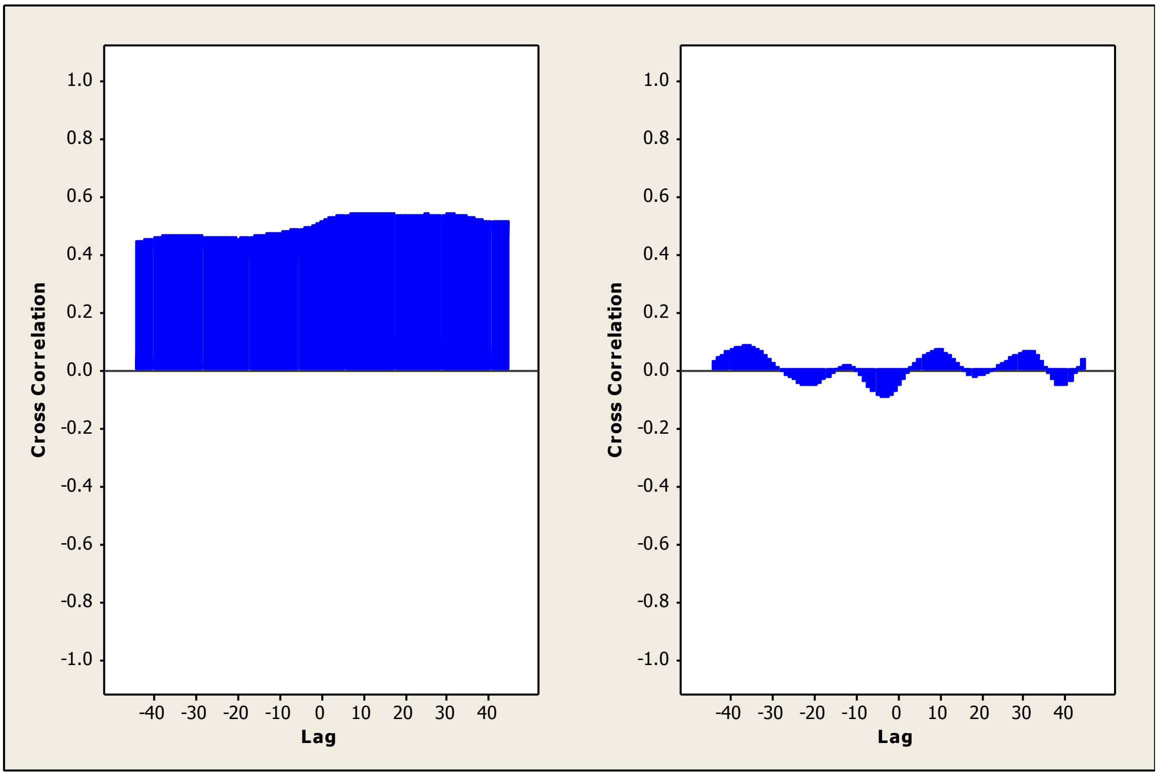
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

2003



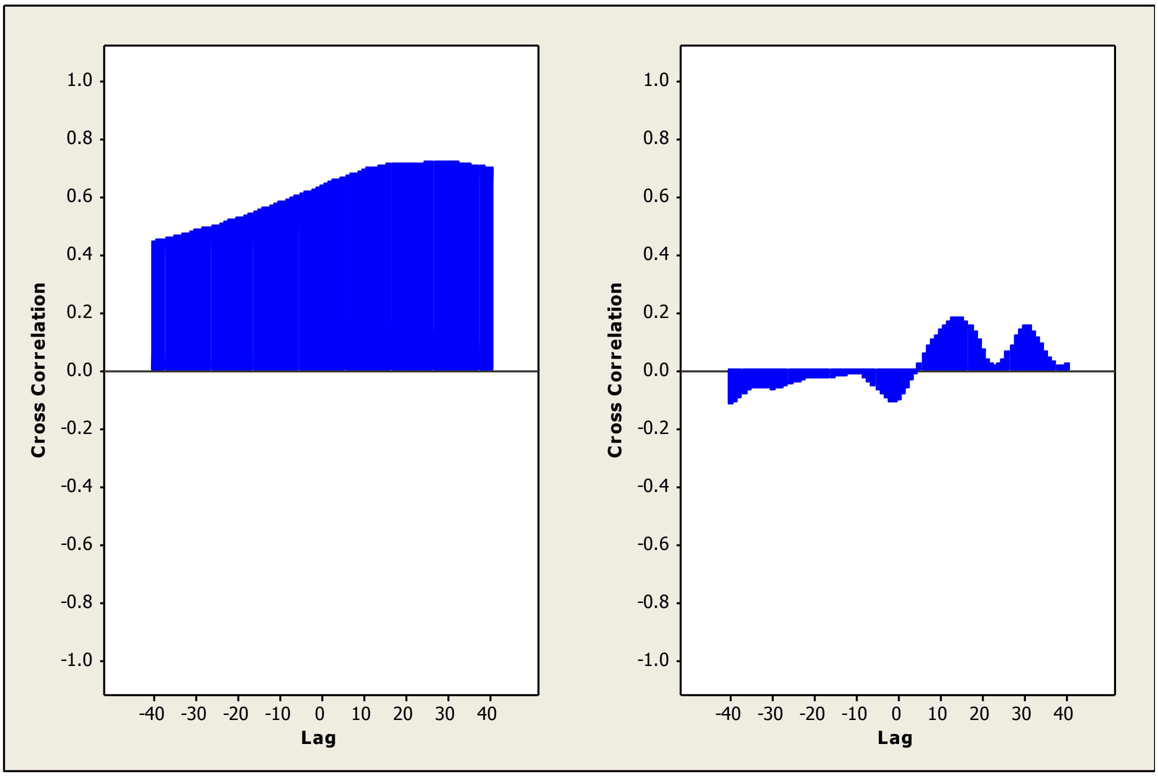
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

2005



Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag
Cross Correlation
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-40 -30 -20 -10 0 10 20 30 40
Lag

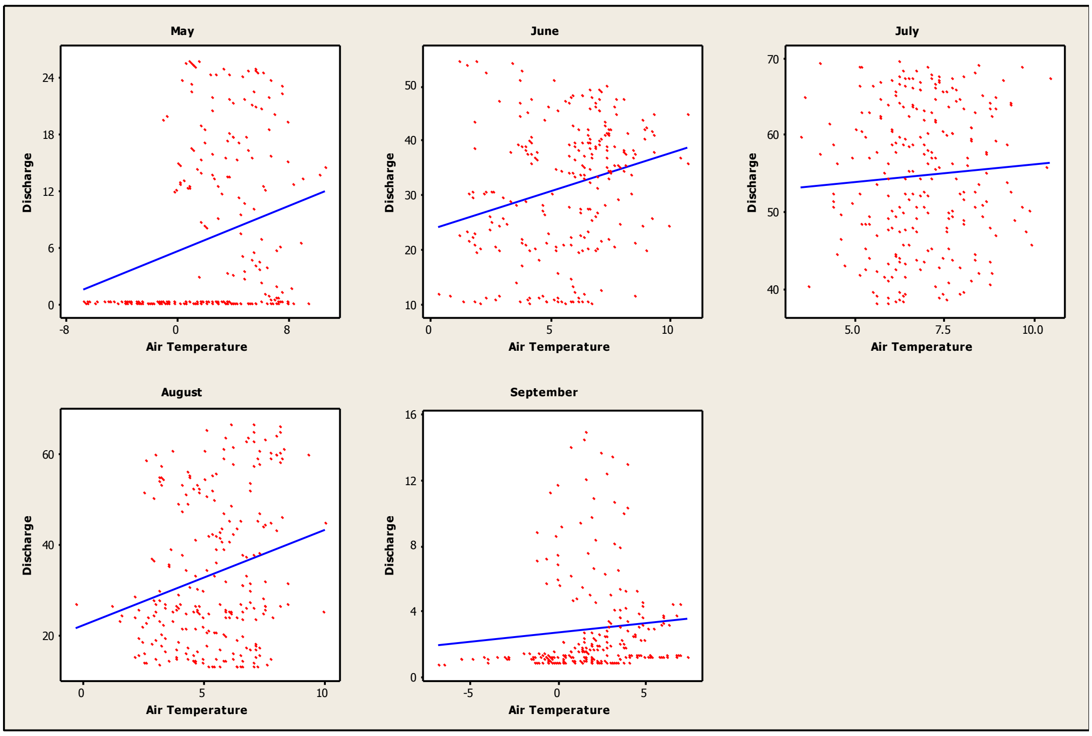
2007


1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Cross Correlation
-40 -30 -20 -10 0 10 20 30 40
Lag
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Cross Correlation
-40 -30 -20 -10 0 10 20 30 40
Lag

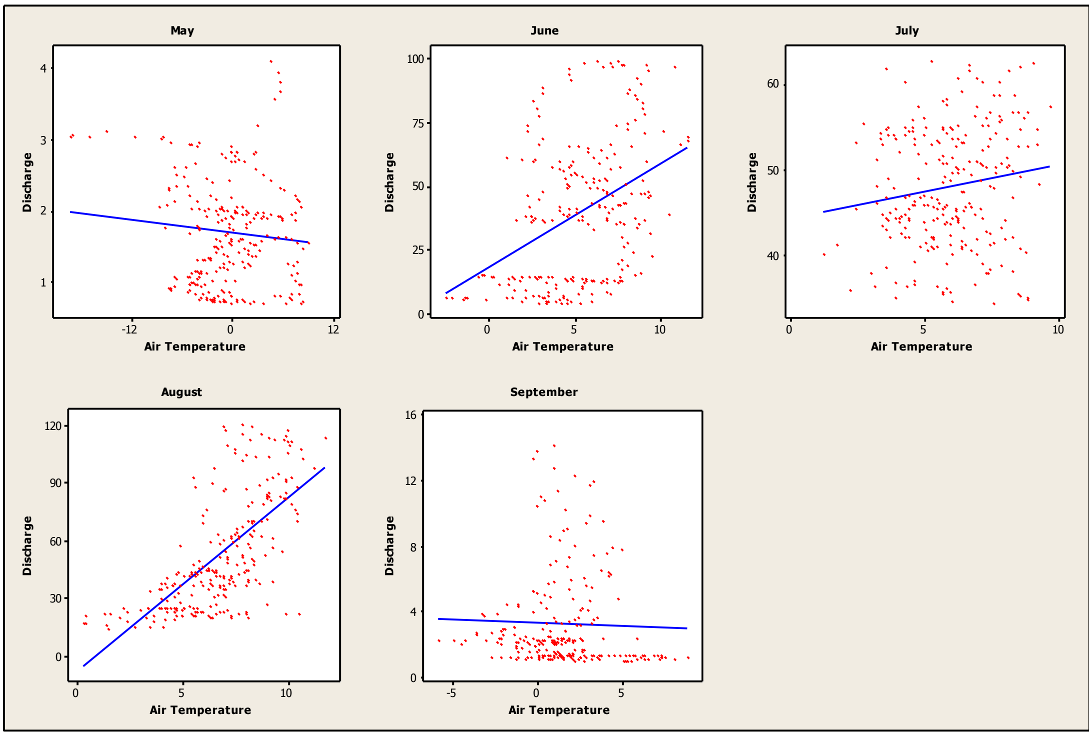
Appendix 4

Individual seasons were broken down into monthly time periods and scatter graphs were plotted, due to the large number of graphs, they were put here in the appendix.

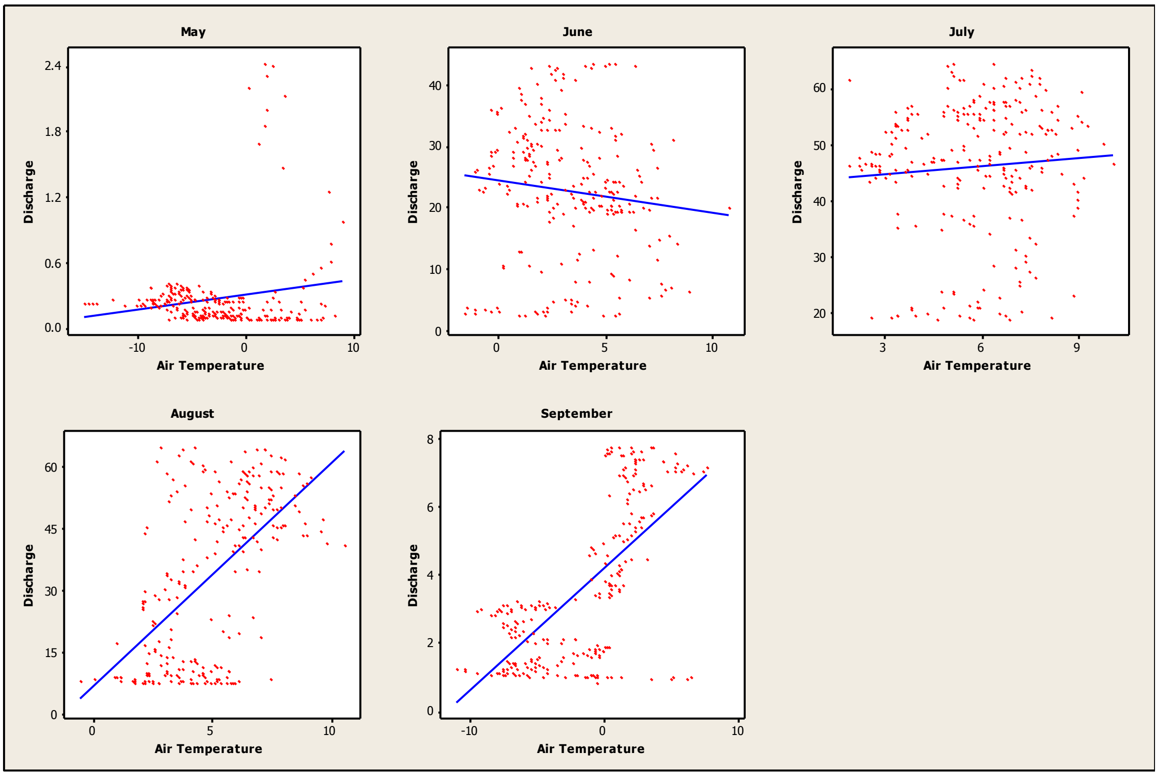
1985



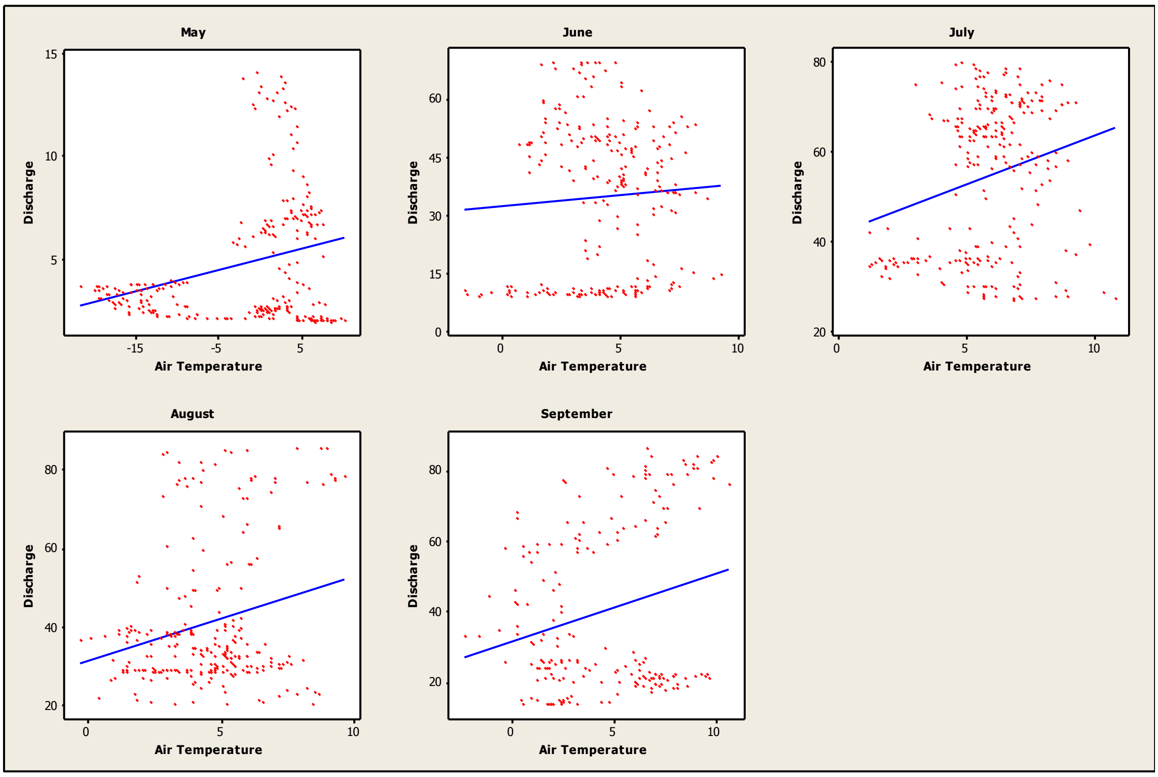
1987



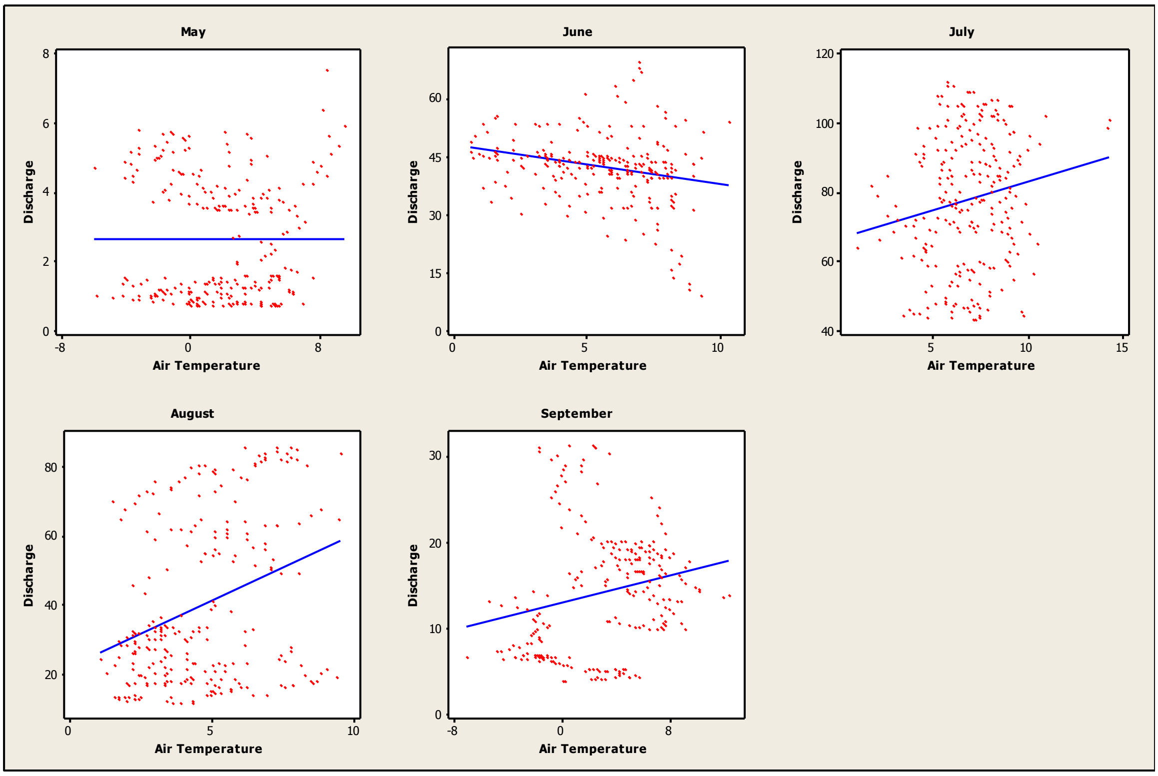
1989


May
June
July
August
September
Discharge
Air Temperature

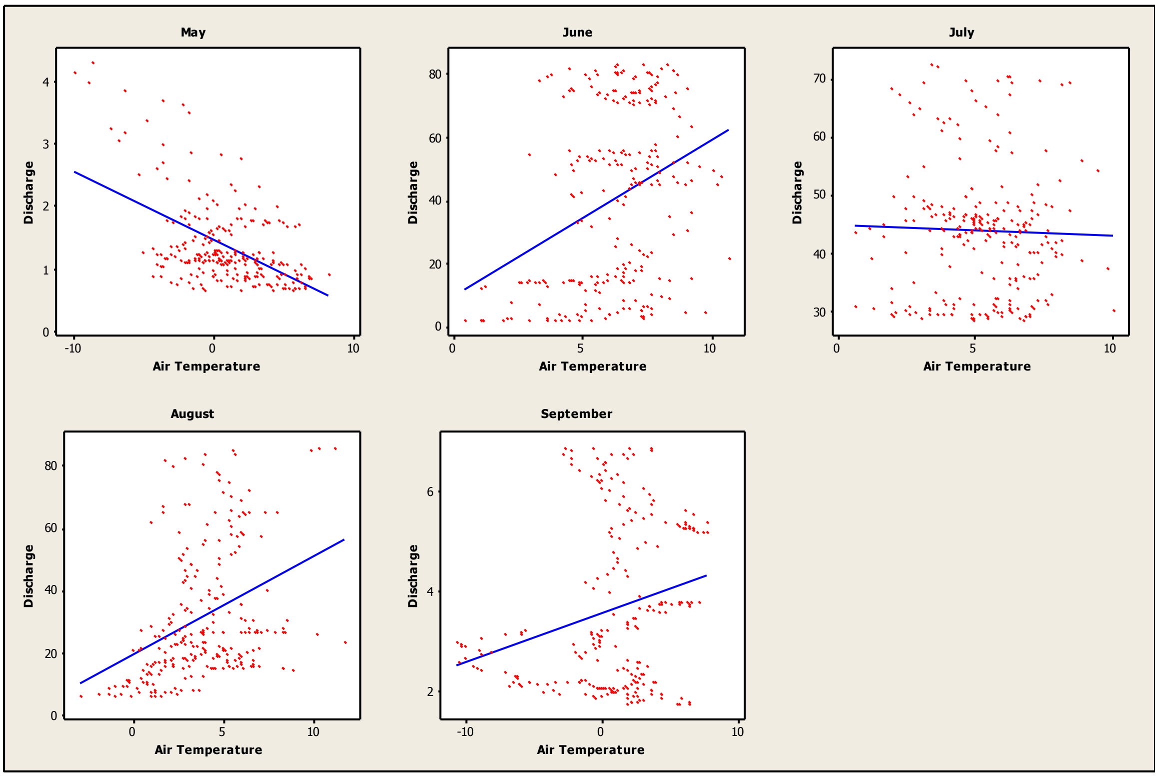
1993


May
June
July
August
September
Discharge
Air Temperature

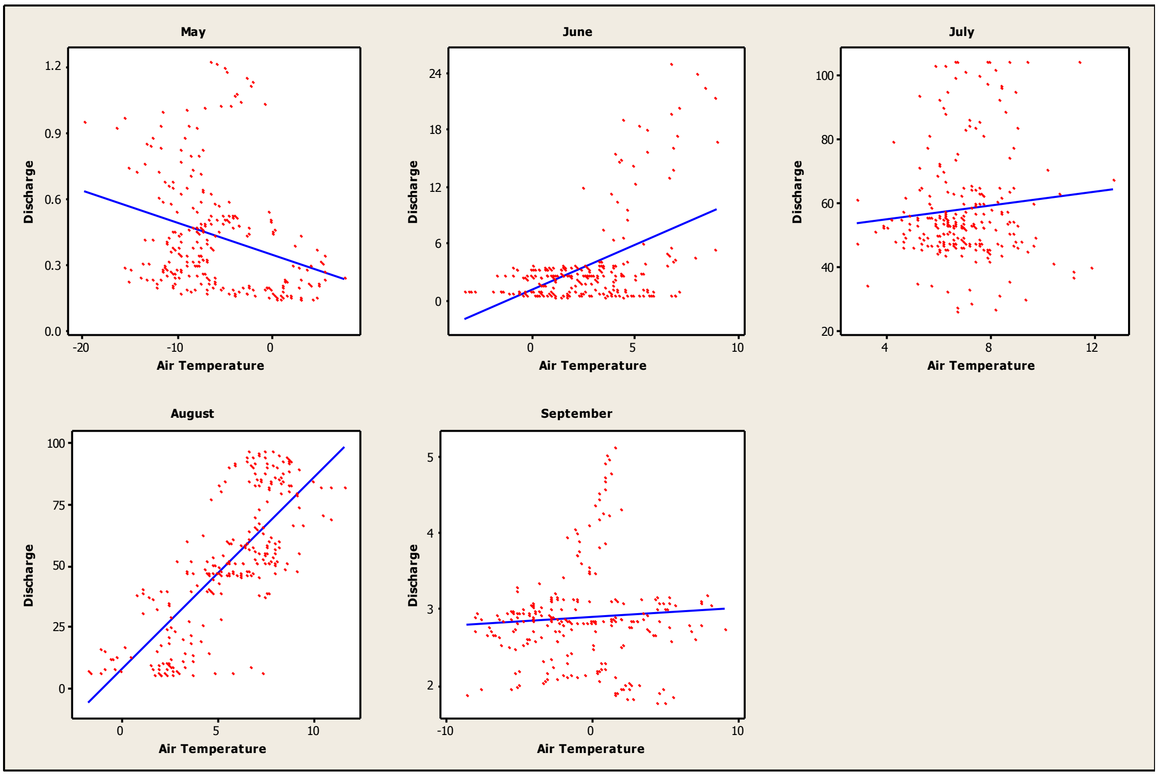
1995


May
June
July
August
September
Discharge
Air Temperature

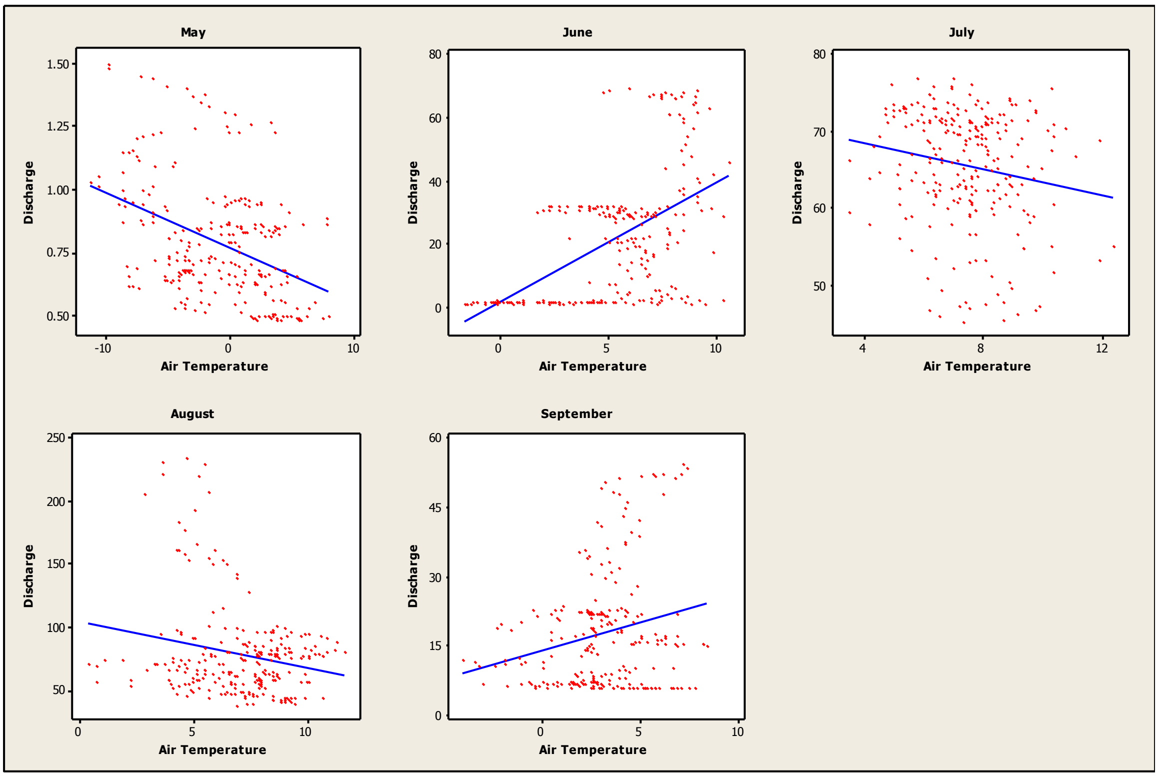
1997


May
June
July
August
September
Discharge
Air Temperature

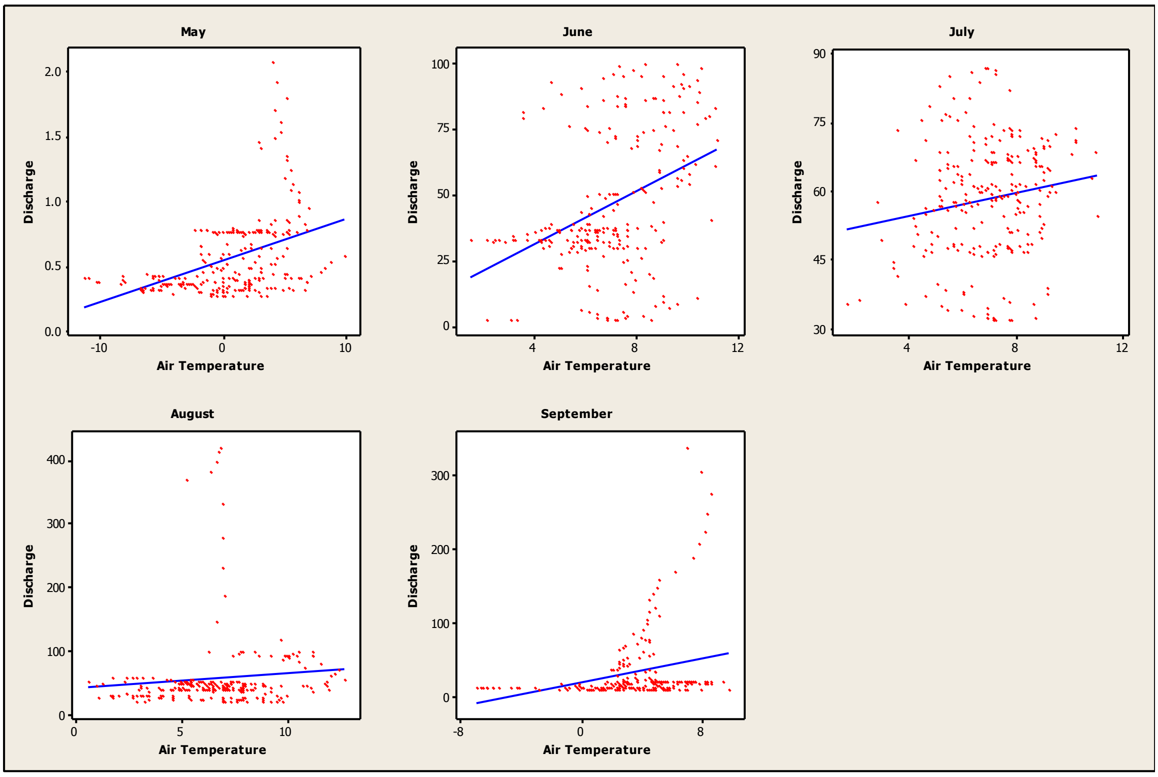
1999


May
June
July
August
September
Discharge
Air Temperature

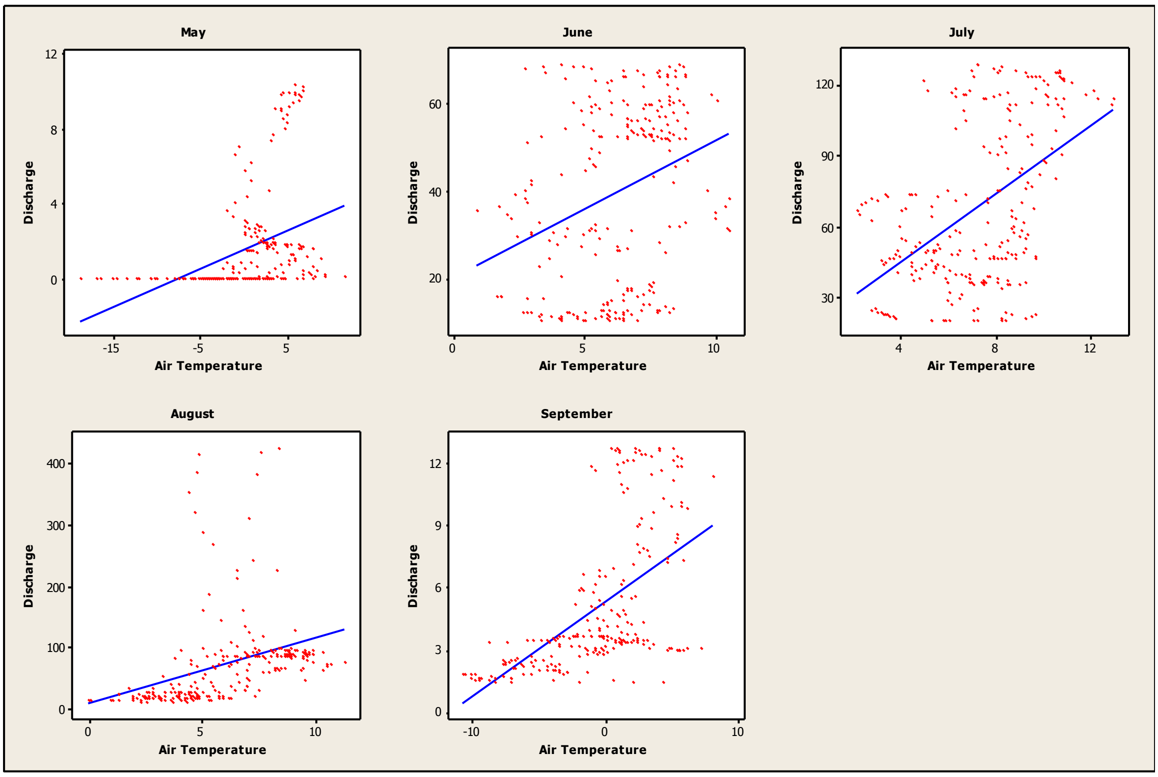
2001


May
June
July
August
September
Discharge
Air Temperature

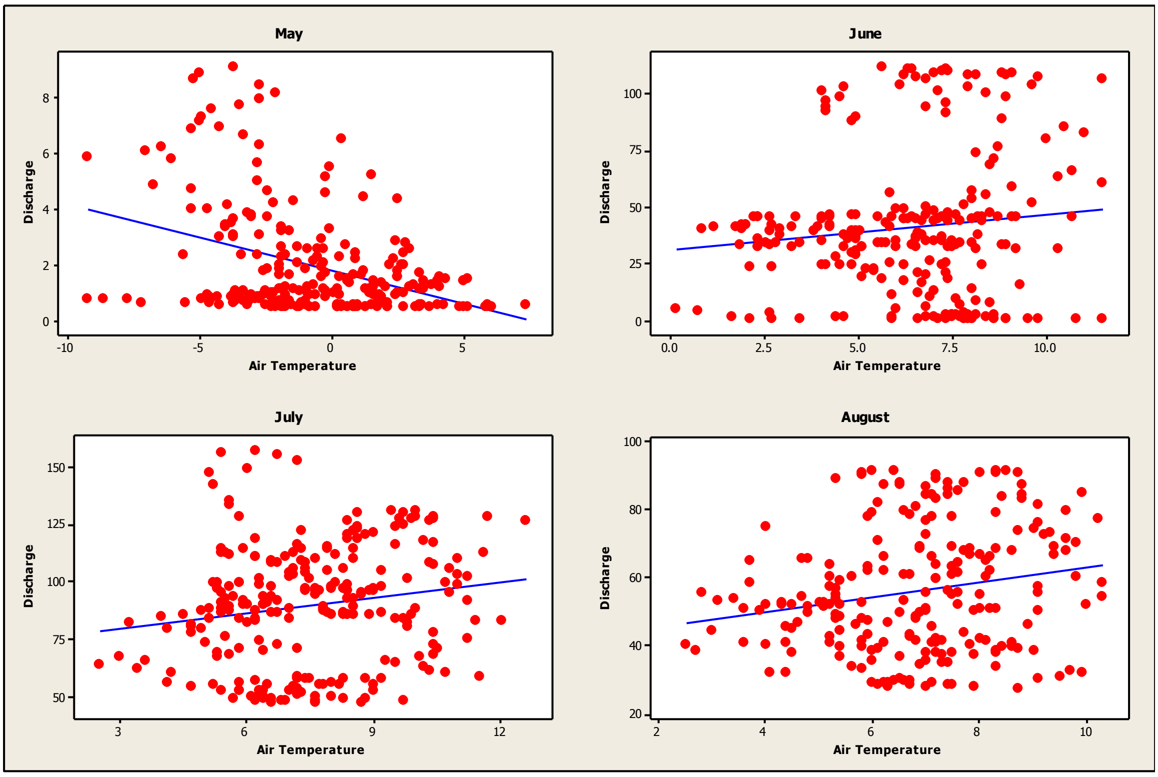
2003


May
June
July
August
September
Discharge
Air Temperature
2.0
1.5
1.0
0.5
0.0
-10
0
10
100
75
50
25
0
4
8
12
90
75
60
45
30
400
300
200
100
5
-8

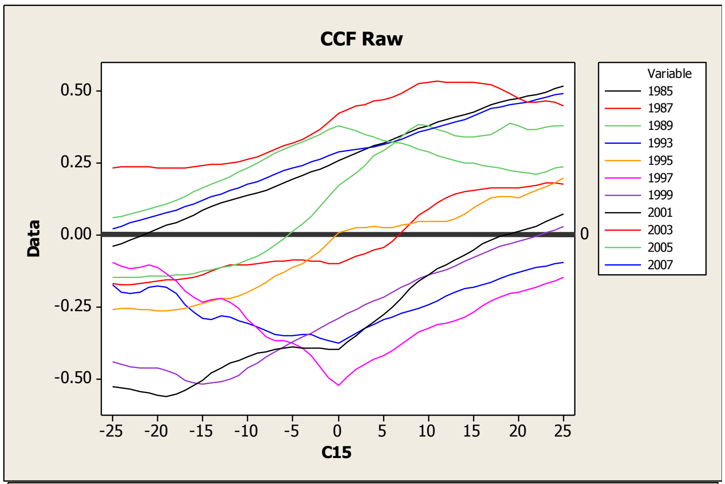
2005

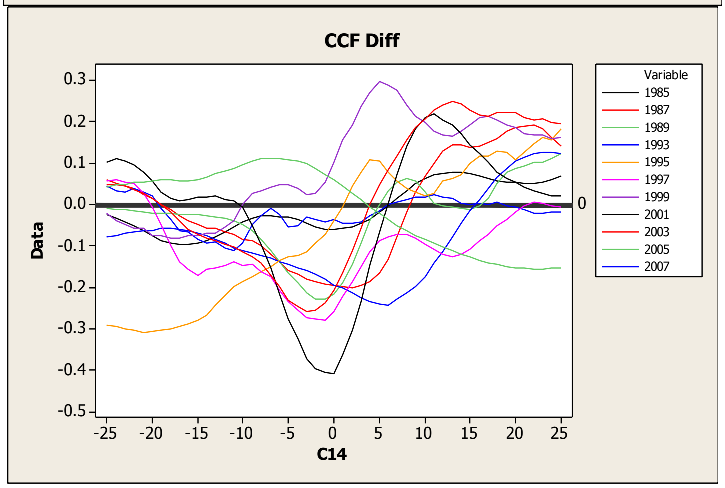

May
June
July
August
September
Discharge
Air Temperature
12
8
4
0
-15
-5
5
60
40
20
10
120
90
30
400
300
200
100
9
6
3
-10

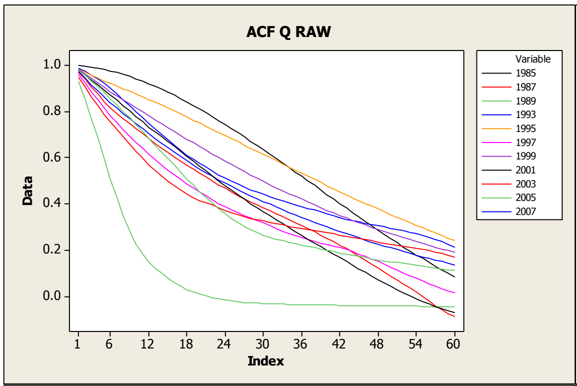
2007

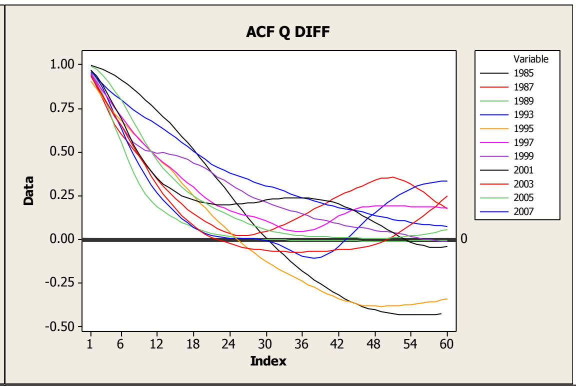


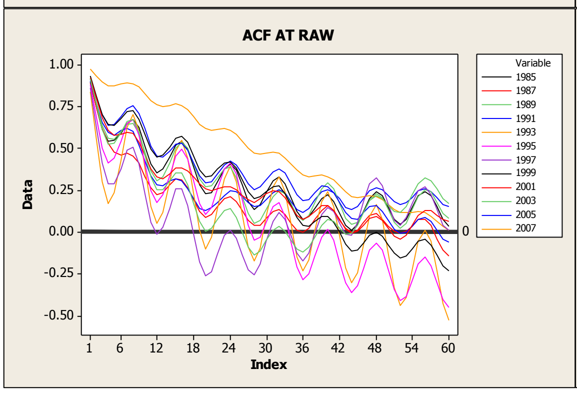
Appendix 5: May

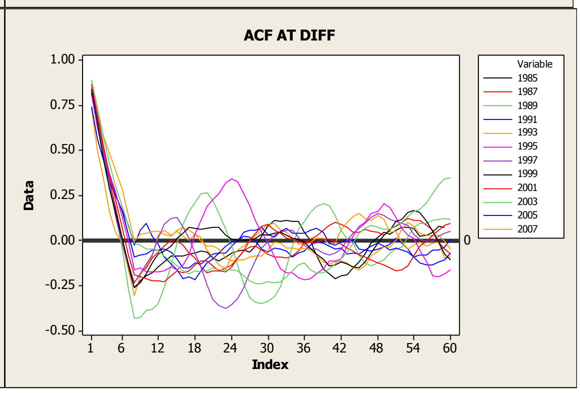




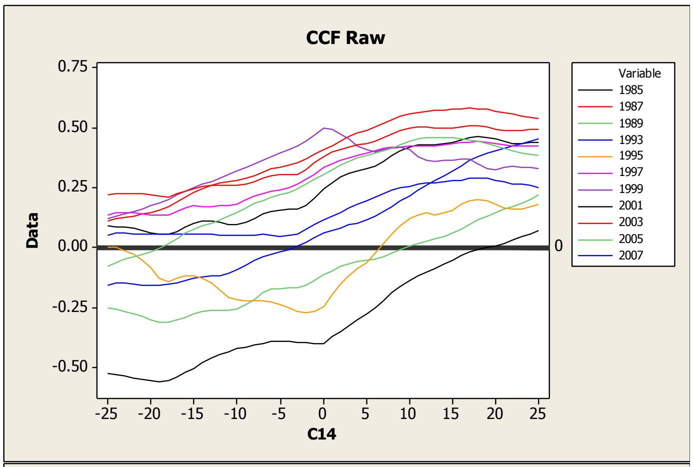


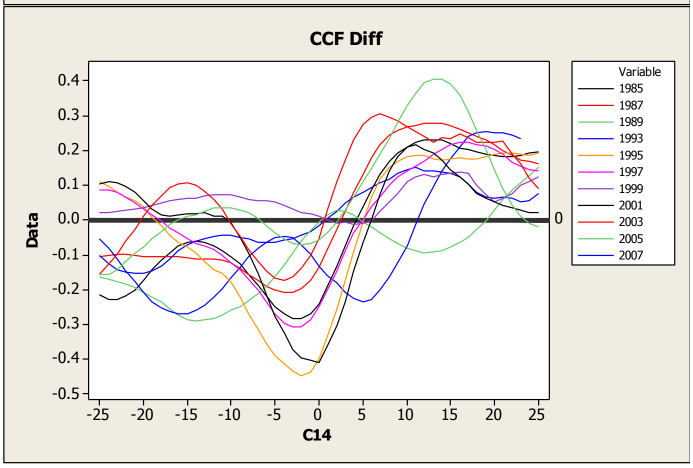


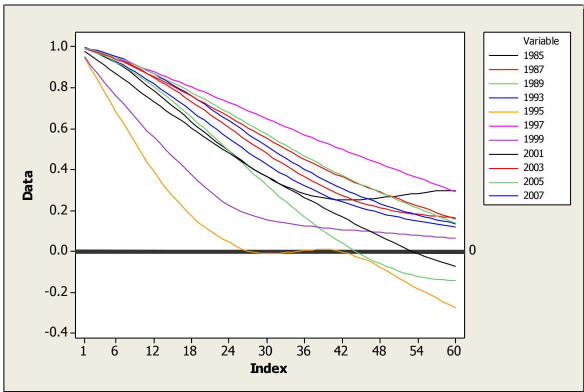


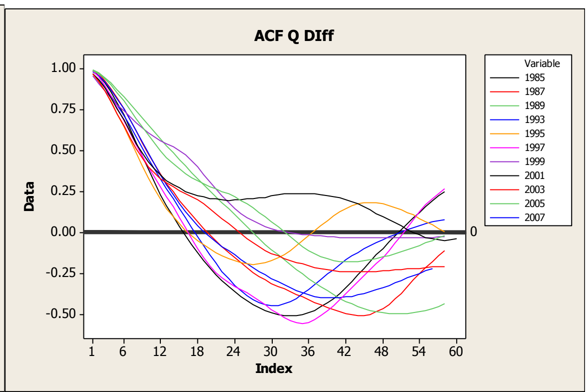


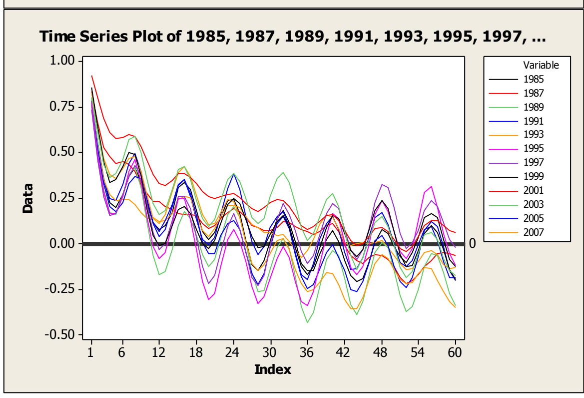
June

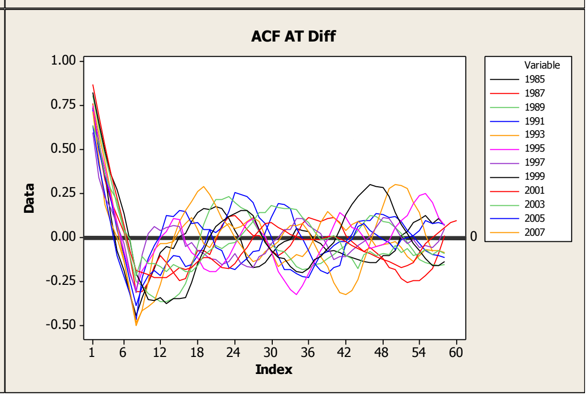

CCF Raw
Data
C14
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007


CCF Diff
Data
C14
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

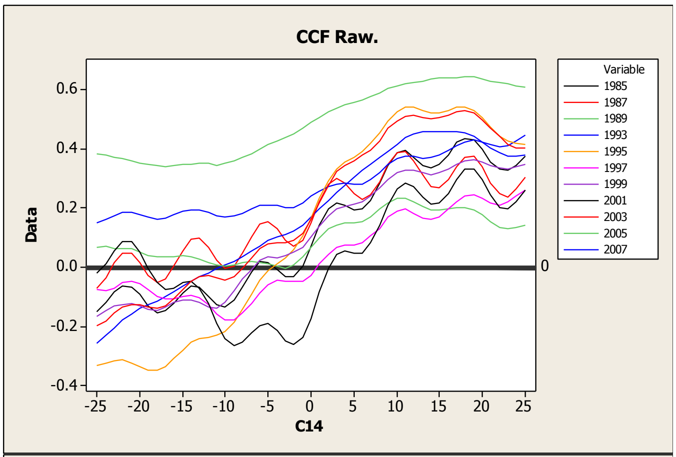

Data
Index
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

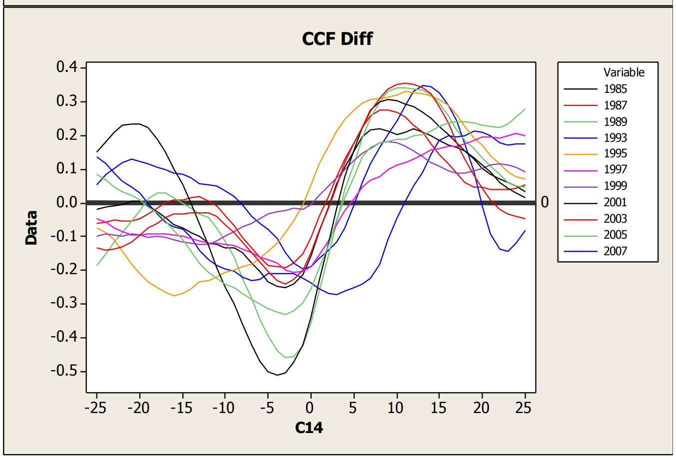

ACF Q DIff
Data
Index
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

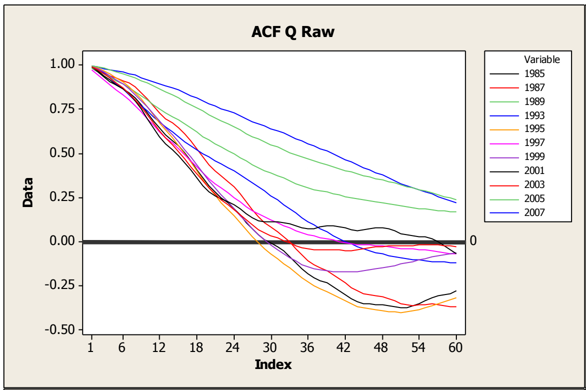

Time Series Plot of 1985, 1987, 1989, 1991, 1993, 1995, 1997, ...
Data
Index
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007

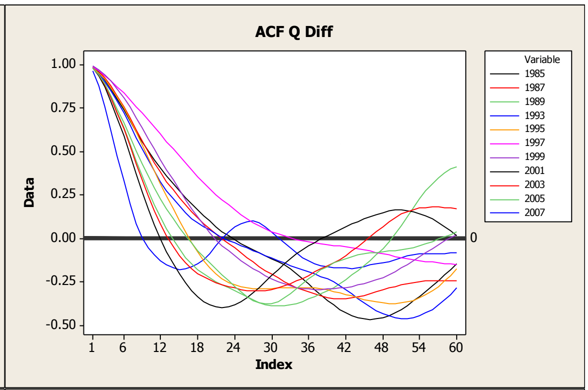

ACF AT Diff
Data
Index
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007

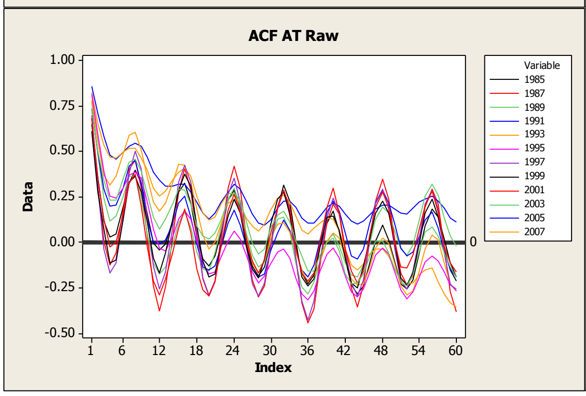
July

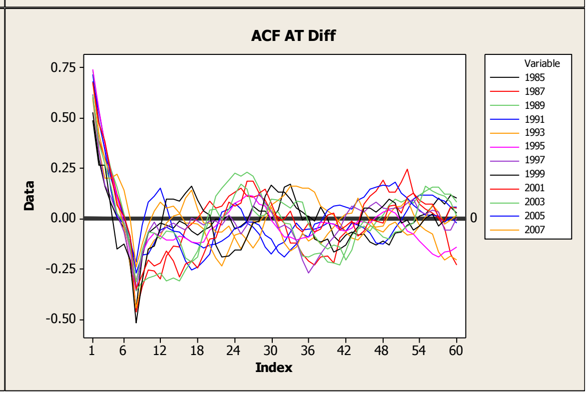

CCF Raw.
Data
C14
0.6
0.4
0.2
0.0
-0.2
-0.4
-25 -20 -15 -10 -5 0 5 10 15 20 25
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007


CCF Diff
Data
C14
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-25 -20 -15 -10 -5 0 5 10 15 20 25
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

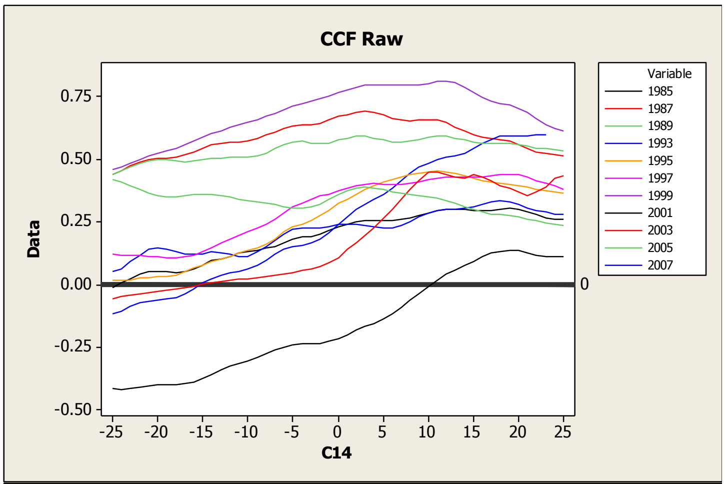

ACF Q Raw
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54 60
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

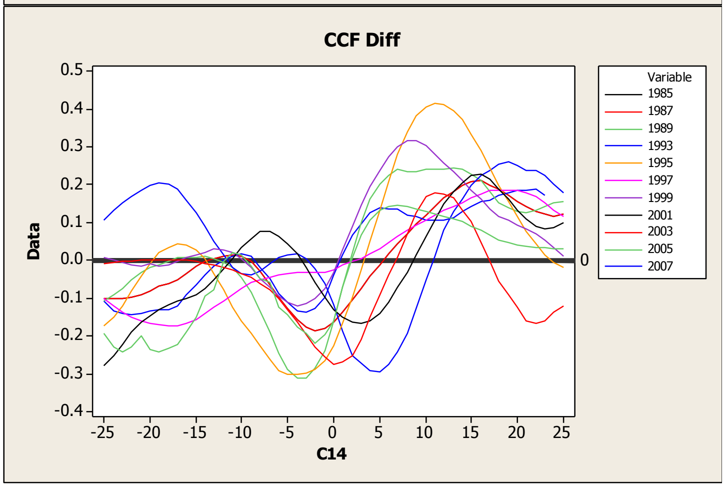

ACF Q Diff
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54 60
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

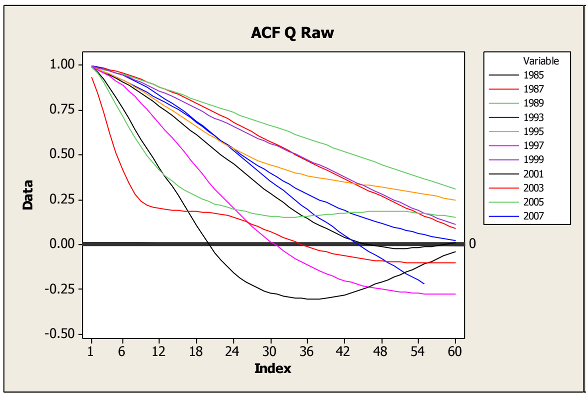

ACF AT Raw
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54 60
0
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007

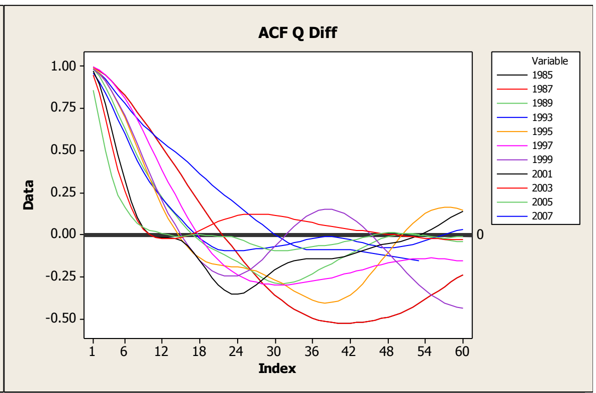

ACF AT Diff
Data
Index
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54 60
0
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007

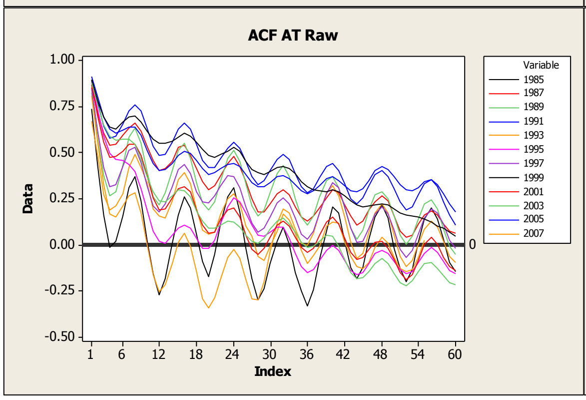
August

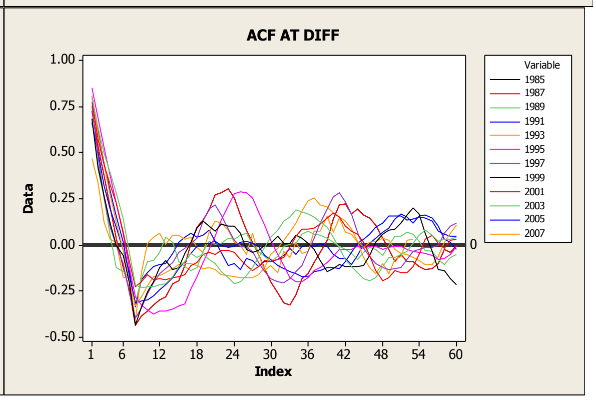

CCF Raw
Data
C14
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007


CCF Diff
Data
C14
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005
2007

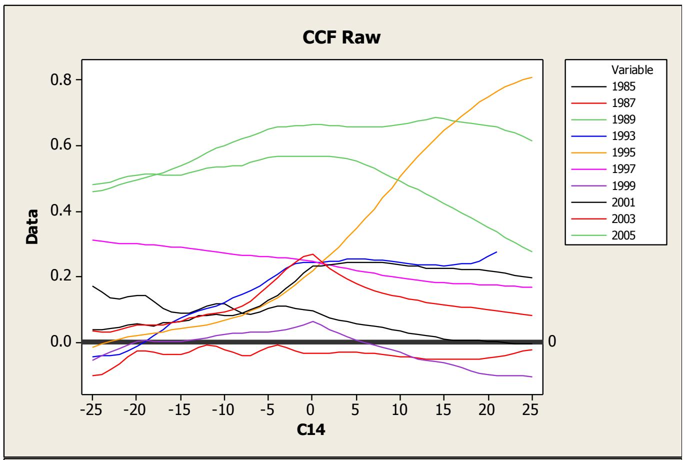

ACF Q Raw
Data
Index

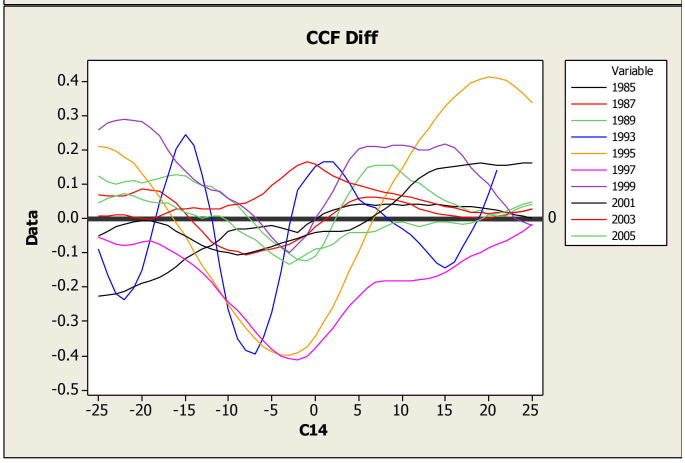

ACF Q Diff
Data
Index

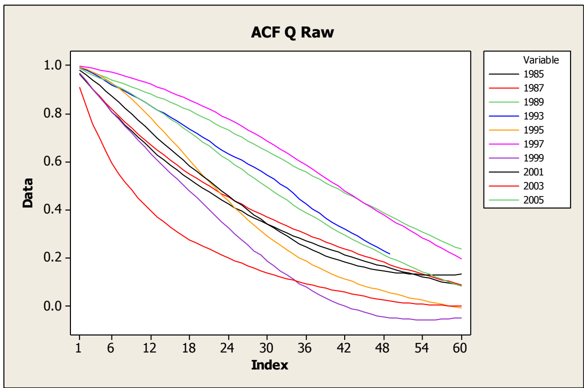

ACF AT Raw
Data
Index

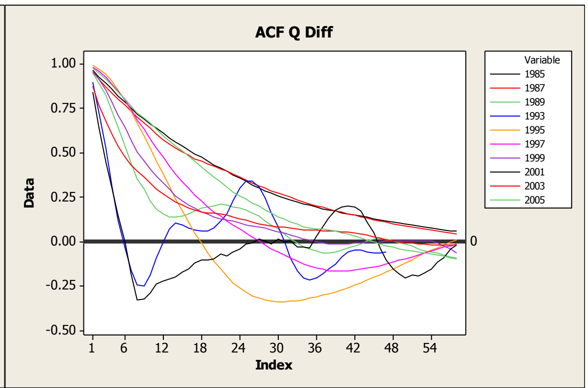

ACF AT DIFF
Data
Index

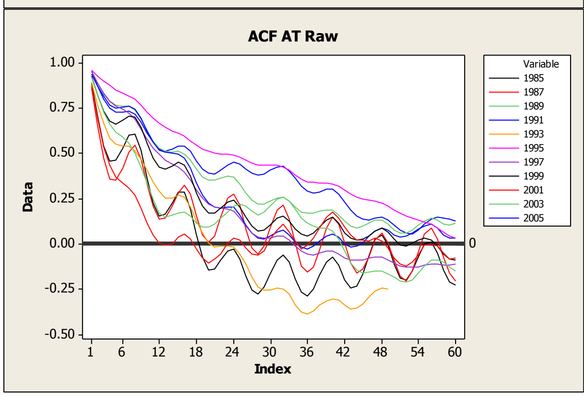
September

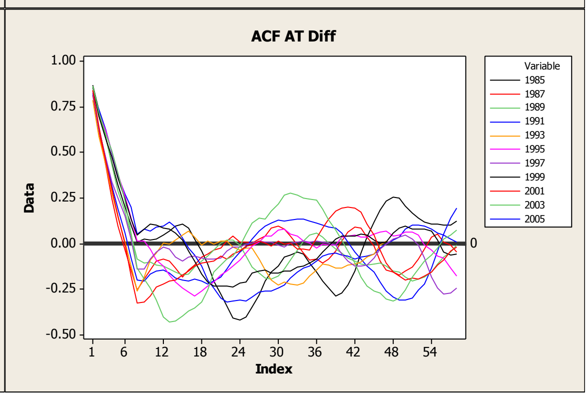

CCF Raw
Data
C14
0.8
0.6
0.4
0.2
0.0
-25 -20 -15 -10 -5 0 5 10 15 20 25
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005


CCF Diff
Data
C14
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-25 -20 -15 -10 -5 0 5 10 15 20 25
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005


ACF Q Raw
Data
Index
1.0
0.8
0.6
0.4
0.2
0.0
1 6 12 18 24 30 36 42 48 54 60
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005


ACF Q Diff
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54
0
Variable
1985
1987
1989
1993
1995
1997
1999
2001
2003
2005


ACF AT Raw
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54 60
0
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005


ACF AT Diff
Data
Index
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
1 6 12 18 24 30 36 42 48 54
0
Variable
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005